# MMC-BASED CONVERTERS FOR MVDC APPLICATIONS

**Prof. Dražen Dujić, Dr. Alexandre Christe, Stefan Milovanović**

École Polytechnique Fédérale de Lausanne (EPFL)
Power Electronics Laboratory
Switzerland

# INTRODUCTION

*Non technical one...*

# INSTRUCTORS

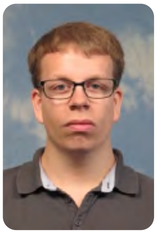
**Prof. Drazen Dujic**

Experience:

| | |
|---|---|
| 2014 – today | École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland |
| 2013 – 2014 | ABB Medium Voltage Drives, Turgi, Switzerland |
| 2009 – 2013 | ABB Corporate Research, Baden-Dättwil, Switzerland |
| 2006 – 2009 | Liverpoool John Moores University, Liverpool, United Kingdom |
| 2003 – 2006 | University of Novi Sad, Novi Sad, Serbia |

Education:

| | |
|---|---|
| 2008 | PhD, Liverpoool John Moores University, Liverpool, United Kingdom |
| 2005 | M.Sc., University of Novi Sad, Novi Sad, Serbia |
| 2002 | Dipl. Ing., University of Novi Sad, Novi Sad, Serbia |



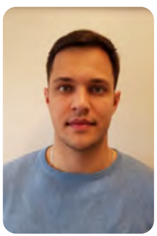
**Dr. Alexandre Christe**

Experience:

| | |
|---|---|
| 2018 – today | ABB Corporate Research, Västerås, Sweden |

Education:

| | |
|---|---|
| 2018 | PhD, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland |
| 2014 | M.Sc., École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland |



**Mr. Stefan Milovanovic**

Education:

| | |
|---|---|
| Pending | PhD, École Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland |
| 2016 | M.Sc., School of Electrical Engineering, University of Belgrade, Belgrade, Serbia |

# POWER ELECTRONICS LABORATORY AT EPFL

École Polytechnique Fédérale de Lausanne

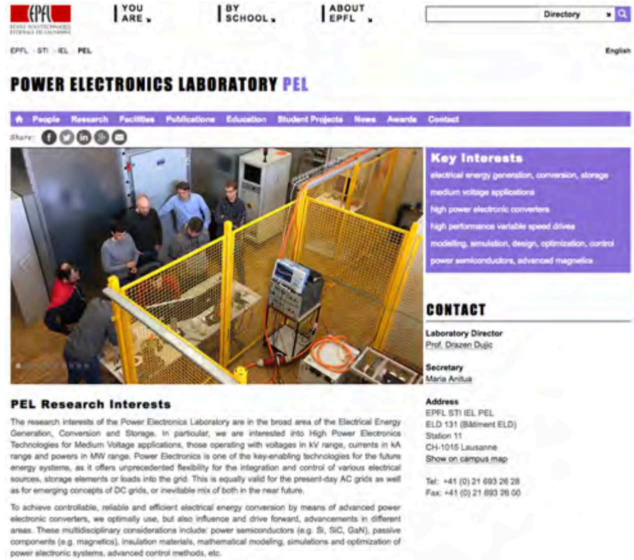
School of Engineering

**EPFL — STI — IEL — PEL**

Institute of Electrical Engineering

- Online since February 2014
- 12 PhD, 1 Scientist, 1 Postdoc, 1 Secretary
- `http://pel.epfl.ch`

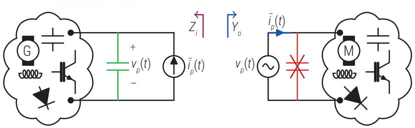
Competence Centre



## MVDC Technologies and Systems

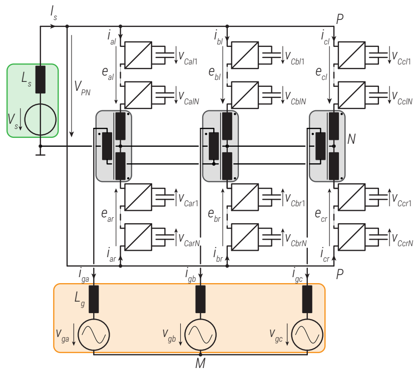
- System Stability
- Protection Coordination
- Power Electronic Converters

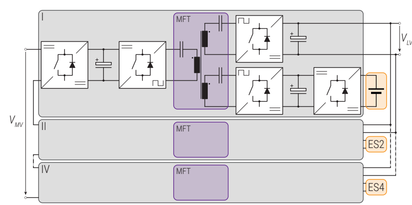
MVDC
ENERGY CONVERSION TECHNOLOGIES AND SYSTEMS




## High Power Electronics

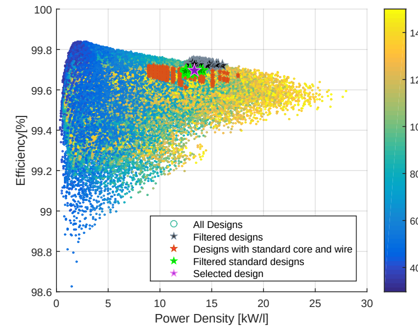
- Multilevel Converters
- Solid State Transformers
- Medium Frequency Conversion




## Characterization

- Semiconductor devices
- Magnetic components
- Systems




# SCHEDULE

**Before the Coffee Break**

**1) Introduction and Motivation**
- Medium Voltage Direct Current Applications
- Modular Multilevel Converters
- Solid State Transformers

**2) Modular Multilevel Converter**
- Operating principles
- Pulse Width Modulation
- Control

**3) Galvanically Isolated Modular Converter**
- Magnetic Integration
- Design Optimization
- Sub-Module Design

**After the Coffee Break**

**4) High Power DC-DC Conversion**
- Dual Active Bridge Converters
- Resonant Converters
- Medium Frequency Conversion

**5) Medium Voltage DC-DC Conversion**
- MMC-based Conversion
- Quasi-Two-Level Converters
- Design and Control

**6) MMC-Based DC-DC Converters**
- Scott Transformer Connection
- Bidirectional vs. Unidirectional
- Design and Control

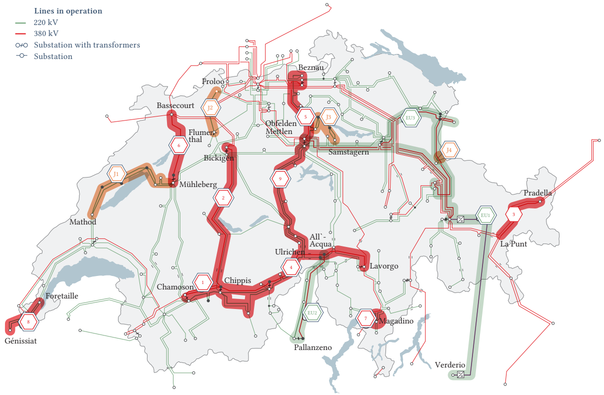
⇒ Tutorial pdf can be downloaded from: *(Source: `https://pel.epfl.ch/publications_talks_en`)*

# MVDC TECHNOLOGIES AND SYSTEMS

*Future electrical energy generation, conversion and storage technologies*

## SwissGrid infrastructure

- Existing infrastructure (220 – 380kV, 50 Hz) is ageing (2/3 built ~ 1960)
- Large PHSPs commissioned ⇒ sufficient capacity required
- Lengthy procedures for new overhead lines construction (low social acceptance, impact on landscape)

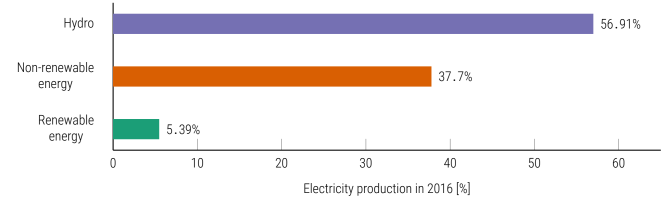



## MVDC grids

- Might be a good candidate w/ underground cable
- Suited for medium-scale energy collection

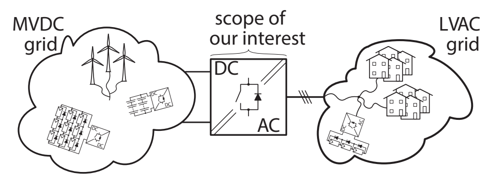
## Swiss energy landscape

- Annual consumption 60 TWh
- Nuclear phase out by 2050




## Swiss Competence Centers for Energy Research (SCCERs)

- Government supported initiative
- SCCER-FURIES for future grids
- Explore ways to interconnect a MVDC grid w/ a LVAC grid



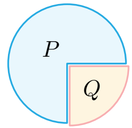

▲ Future energy systems with MVDC and LVAC grids

# WHY DC?

- No reactive power

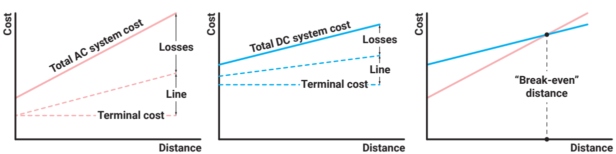
Example: @ $cos(\varphi) = 0.95$

$$\boxed{\frac{P}{Q} \approx \frac{3}{1}}$$

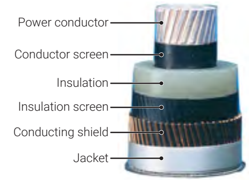


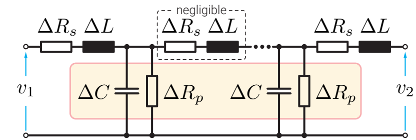

  - No constraints imposed upon transmission distance
  - Transmission capacity increase
  - Lower transmission losses
  - Alleviated stability problems

- No skin effect ($R_\gamma \downarrow \Rightarrow P_\gamma \uparrow$)
- Cheaper solution ("Break-even distance")
- Underwater cable transmission
- No need for synchronization (Marine applications)
- Direct integration of Renewable Energy Sources
- Challenges $\Rightarrow$ DC Transformer/Protection?

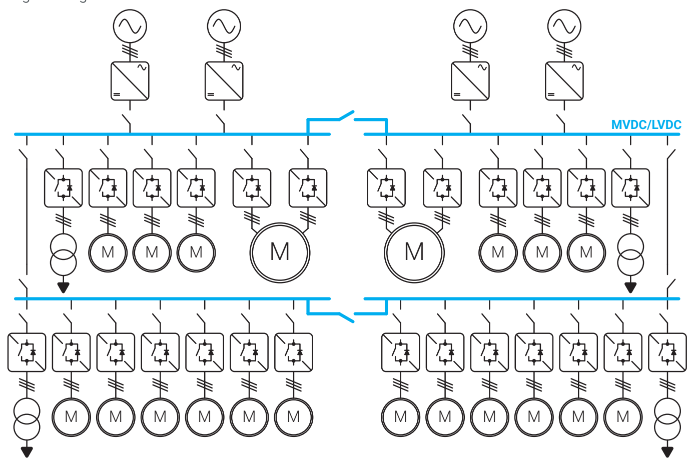



▲ Cost comparison between AC and DC systems




▲ High voltage cable




▲ DC Ship distribution system - frequency decoupling through a DC distribution

# TREND TOWARDS DC

## Bulk power transmission

- Break even distance against AC lines
- ~ 50 km for subsea cables or 600 km for overhead lines
- Long history since 1950s
- Interconnection of asynchronous grids

▲ From mercury arc rectifiers to modern HVDC systems

## LVDC ships

- Variable frequency generators ⇒ maximum efficiency of the internal combustion engines
- Commercial products by ABB & Siemens

▲ Specialized vessels with LVDC distribution

## Datacenters

- 380 $V_{dc}$
- DC loads (including UPS)
- Expected efficiency increase

## Large PV powerplants

- 1500 $V_{dc}$ PV central inverters
- Higher number of series-connected panels per string

▲ 1500V PV inverter - step towards the MVDC

## Open challenges

- DC breaker
- Conversion blocks missing
- Protection coordination

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▲ 1500V PV inverter - step towards the MVDC

⇒ dc beneficial for medium / high power applications

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# EMERGING MVDC APPLICATIONS

**Installations**

- ABB HVDC Light demo: 4.3 km/$\pm$9 $kV_{dc}$ [1]
- Tidal power connection: 16 km/10 $kV_{dc}$ (based on MV3000 & MV7000) [2]

- Unidirectional oil platform connection in China: 29.2 km/$\pm$15 $kV_{dc}$ [3]

**Projects**

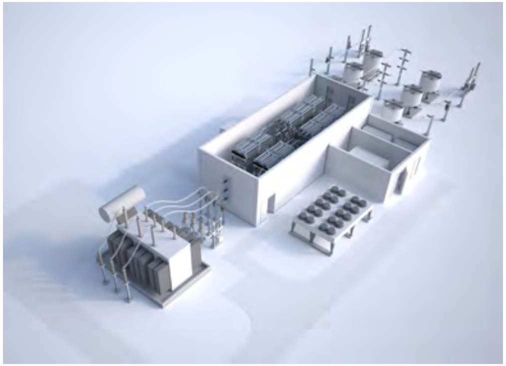
- Angle DC: conversion of 33 kV MVac line to $\pm$27 kV MVdc [4]

**Universities**

- Increased number of laboratories active in high power domain
- China, Europe, USA,...

**Products**

- Siemens MVDC Plus
  - 30 - 150 MW
  - < 200 km
  - < $\pm$50 $kV_{dc}$



- RXPE Smart VSC-MVDC
  - 1 - 10 MVAr
  - $\pm$5 - $\pm$50 $kV_{dc}$
  - 40 - 200 km

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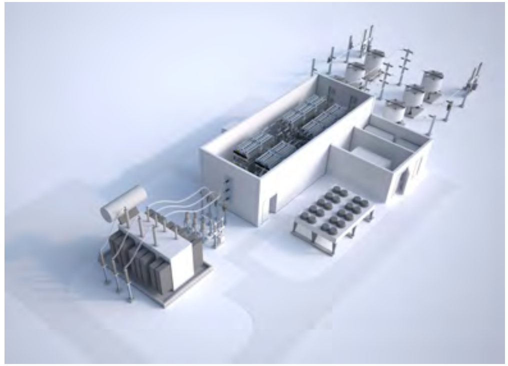

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  - 1 - 10 MVAr
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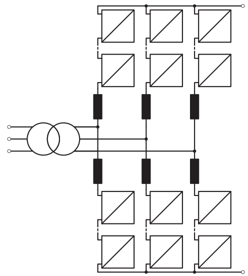
⇒ MVDC is gaining momentum!

# TREND TOWARDS HIGHLY MODULAR CONVERTER TOPOLOGIES

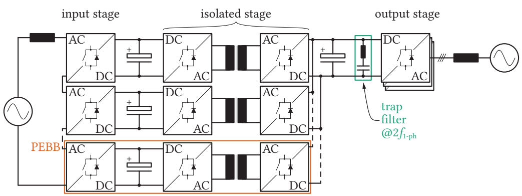
## HVDC

- Decoupled semiconductor switching frequency from converter apparent switching frequency
- Improved harmonic performance ⇒ less / no filters
- Series-connection of semiconductors still possible
- Fault blocking capability depending on cell type



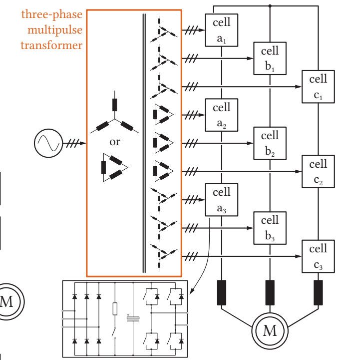
## Solid-state transformers (SSTs)

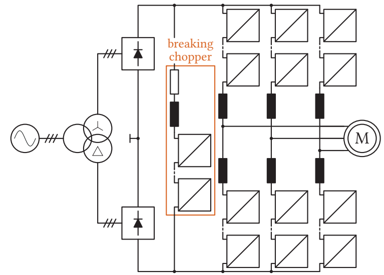
- Power density increase w/ conversion & isolation at higher frequency
- Grid applications / traction transformer w/ different optimization objectives
- MFT design / isolation are the bottlenecks




## MV drives

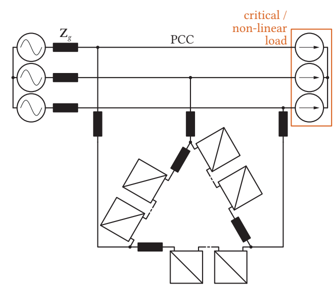
- Monolithic ML topologies (NPC, NPP, FC, ANPC) are not scalable
- Robicon drive → everyone offers it
- Siemens & Benshaw: MMC drive
- Low $dv/dt$ ⇒ motor friendly




## FACTS

- SFC for railway interties (direct catenary connection)
- STATCOM
- BESS (split batteries)



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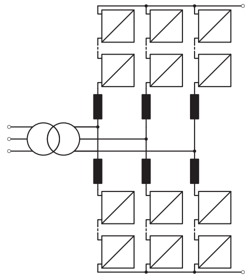

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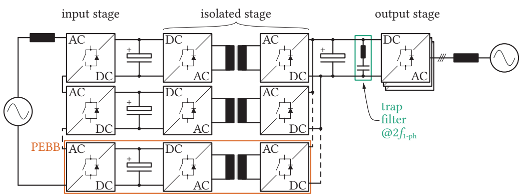


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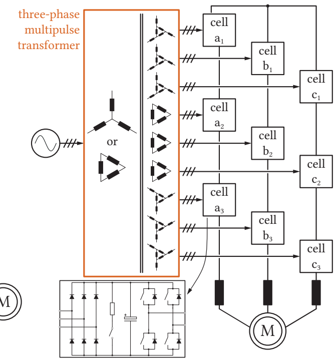


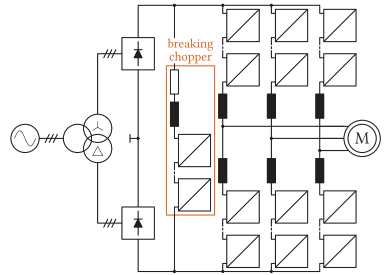


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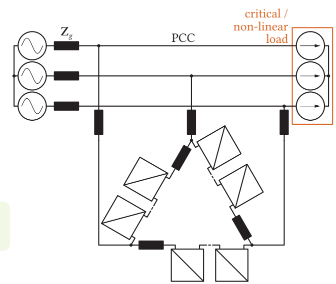



⇒ Modularity provides obvious benefits in high power applications!

# SOLID STATE TRANSFORMER FOR TRACTION (ABB - 1.2MW PETT)

## Characteristics

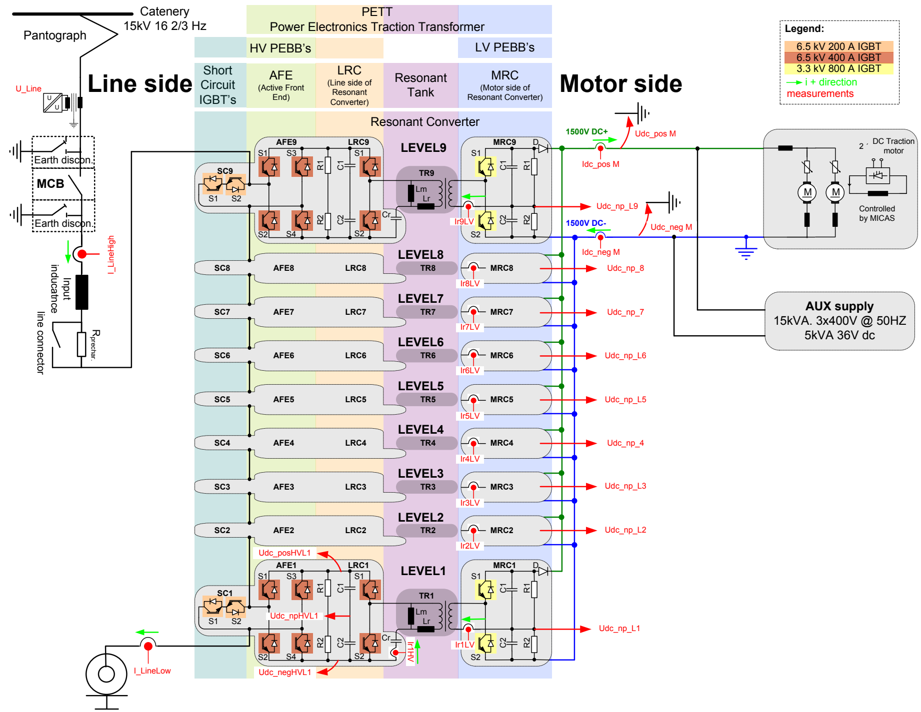
- 1-Phase MVAC to MVDC
- Power: 1.2MVA
- Input AC voltage: 15kV, 16.7Hz
- Output DC voltage: 1500 V
- 9 cascaded stages (n + 1)
- input-series output-parallel
- double stage conversion

## 99 Semiconductor Devices

- HV PEBB: 9 x (6 x 6.5kV IGBT)
- LV PEBB: 9 x (2 x 3.3kV IGBT)
- Bypass: 9 x (2 x 6.5kV IGBT)
- Decoupling: 9 x (1 x 3.3kV Diode)

## 9 MFTs

- Power: 150kW
- Frequency: 1.75kHz
- Core: Nanocrystalline
- Winding: Litz
- Insulation / Cooling: oil




▲ ABB PETT scheme [5], [6]

**Retrofitted to shunting locomotive**

- Replaced LFT + SCR rectifier
- Propulsion motor - 450kW
- 12 months of field service
- No power electronic failures
- Efficiency around 96%
- Weight: ≈ 4.5 t

**Technologies**

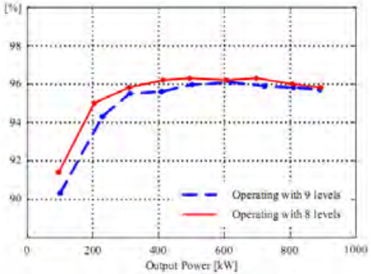
- Standard 3.3kV and 6.5kV IGBTs
- De-ionized water cooling
- Oil cooling/insulation for MFTs
- n + 1 redundancy
- IGBT used for bypass switch

**Displayed at:**

- Swiss Museum of Transport
- https://www.verkehrshaus.ch







▲ ABB PETT prototype [5], [6]

# MEDIUM OR LOW FREQUENCY CONVERSION?

## MVDC integration challenge

- MVDC-LVAC galvanically isolated conversion system

## Desired conversion features

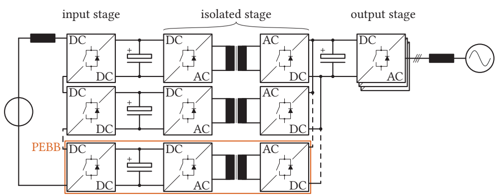
- High efficiency
- Galvanic isolation
- Modularity
- Scalability
- Reliability
- Availability

## Laboratory prototype ratings

- $S = 0.5\,\mathrm{MVA}$
- $N_{\mathrm{cells}} = 6 \times 16$
- $V_{\mathrm{dc}} = 10\,\mathrm{kV}$
- $V_{\mathrm{ac}} = 400\,\mathrm{V}$

## SST approach

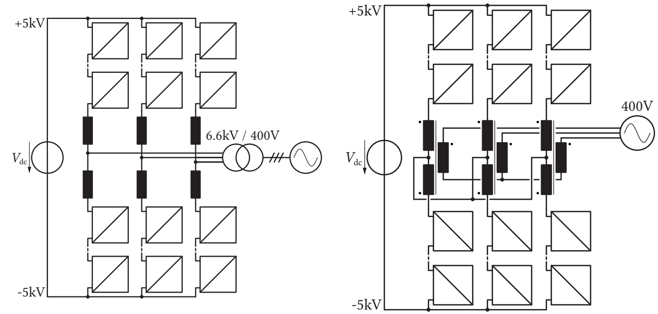
- VSI on LVAC side of SST reduces efficiency by $\approx 2\,\%$ (!) [7]
- Drawn solution is not the unique possibility




▲ Generic SST illustration for MVDC-LVAC conversion

## MMC

- Solution with MMC + LFT has higher efficiency




## Research opportunities

1. MMC topological variations and control methods
2. Modulation and branch balancing methods
3. Integration of branch inductances into the transformer structure: **GIMC**
4. Virtual Submodule Concept for fast cell loss estimation method [8]
5. MMC cell design optimization [9]

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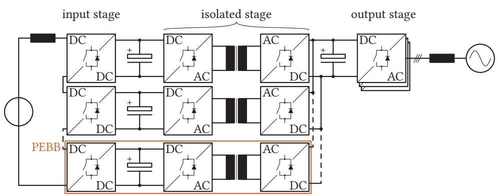


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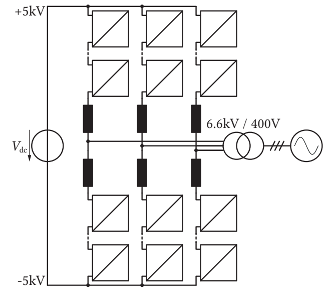


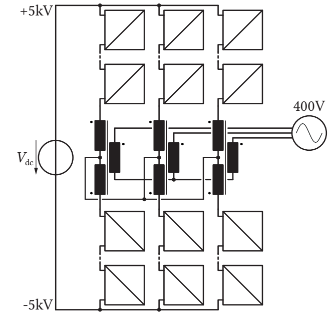


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⇒ The choice is not always obvious and greatly depends on the application requirements and constraints!

# MODULAR MULTILEVEL CONVERTER

*Fundamental operating principles, modeling, power equations*

# NOMENCLATURE

**Cell**

- Controllable devices (semiconductors)
- Energy storage element (capacitor)

**Branch**

- Controllable current / voltage source
- A string of cells
- One reactor

**Phase-leg**

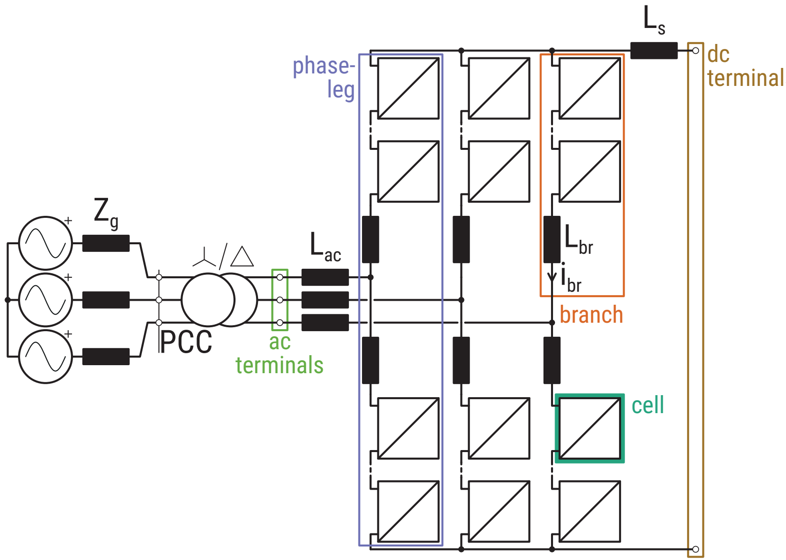
- Comprising two branches

**AC terminals**

- Connection to a grid (with or without transformer) or a load (e.g., ac machine)

**DC terminals**

- Connection to transmission line (overhead line or cable), load or other converter (back-to-back)

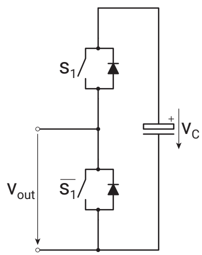


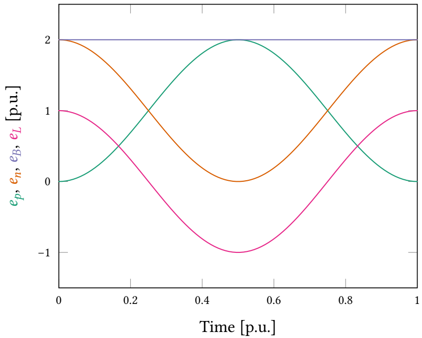

▲ Modular multilevel converter connected to an ac grid through a transformer

Functionality wise, only $L_{br}$ is required!

## Unipolar cell

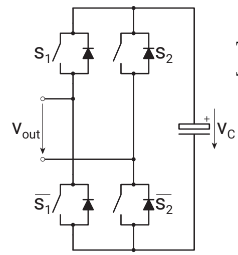
- Best for efficiency
- No fault blocking capability
- 2-level output voltage

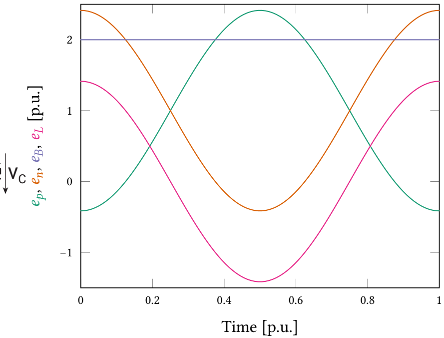



## Bipolar cell

- Fault blocking capability
- Conduction losses double
- 3-level output voltage




Many other variations and advanced cell types have been reported...

**KVL equations**

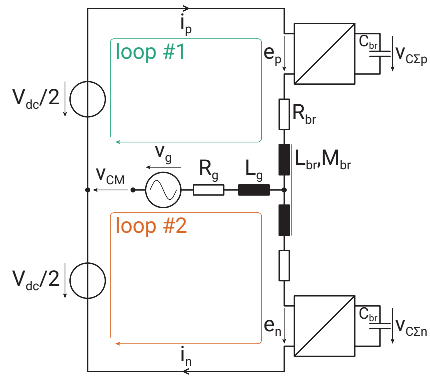
$$\frac{V_{\mathrm{dc}}}{2} = e_p + L_{\mathrm{br}}\frac{\mathrm{d}}{\mathrm{dt}}i_p - M_{\mathrm{br}}\frac{\mathrm{d}}{\mathrm{dt}}i_n + R_{\mathrm{br}}i_p + L_g\frac{\mathrm{d}}{\mathrm{dt}}(i_p - i_n) + R_g(i_p - i_n) + v_g + v_{\mathrm{CM}}$$

$$\frac{V_{\mathrm{dc}}}{2} = e_n + L_{\mathrm{br}}\frac{\mathrm{d}}{\mathrm{dt}}i_n - M_{\mathrm{br}}\frac{\mathrm{d}}{\mathrm{dt}}i_p + R_{\mathrm{br}}i_n - L_g\frac{\mathrm{d}}{\mathrm{dt}}(i_p - i_n) - R_g(i_p - i_n) - v_g - v_{\mathrm{CM}}$$

where $e_x = \sum_{i=1}^{N_{\mathrm{cells}}} s_{xi}v_{Cxi}$ (switched model) or $e_x = m_x v_{C\Sigma x}$ (average model)

**Cell capacitor voltages**

$$\frac{\mathrm{d}}{\mathrm{dt}}\begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n}\end{bmatrix} = \frac{1}{C_{\mathrm{br}}}\begin{bmatrix} m_p & 0 \\ 0 & m_n\end{bmatrix}\begin{bmatrix} i_p \\ i_n\end{bmatrix}$$




▲ Single-phase MMC for modeling

**First transformation**

$$\begin{bmatrix} i_{\mathrm{circ}} \\ i_g\end{bmatrix} = \begin{bmatrix} 1/2 & 1/2 \\ 1 & -1\end{bmatrix}\begin{bmatrix} i_p \\ i_n\end{bmatrix} \quad\leftrightarrow\quad \begin{bmatrix} i_p \\ i_n\end{bmatrix} = \begin{bmatrix} 1 & 1/2 \\ 1 & -1/2\end{bmatrix}\begin{bmatrix} i_{\mathrm{circ}} \\ i_g\end{bmatrix}$$

$$\begin{bmatrix} e_B \\ e_L\end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2\end{bmatrix}\begin{bmatrix} e_p \\ e_n\end{bmatrix} \quad\leftrightarrow\quad \begin{bmatrix} e_p \\ e_n\end{bmatrix} = \begin{bmatrix} 1/2 & -1 \\ 1/2 & 1\end{bmatrix}\begin{bmatrix} e_B \\ e_L\end{bmatrix}$$

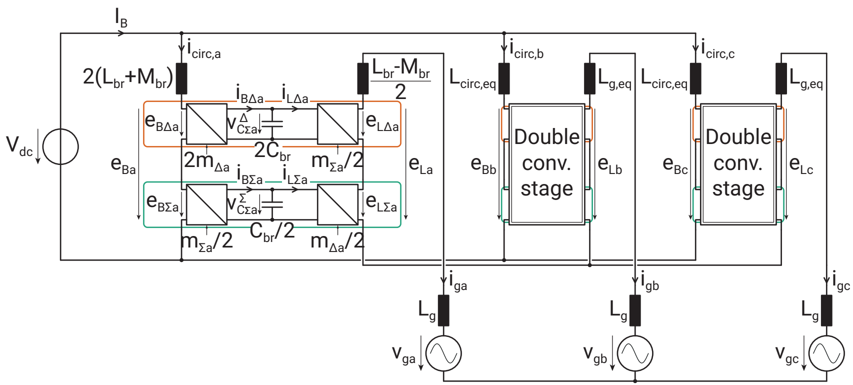
**Second transformation**

$$\begin{bmatrix} v_{C\Sigma}^{\Sigma} \\ v_{C\Sigma}^{\Delta}\end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2\end{bmatrix}\begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n}\end{bmatrix} \quad\leftrightarrow\quad \begin{bmatrix} v_{C\Sigma p} \\ v_{C\Sigma n}\end{bmatrix} = \begin{bmatrix} 1/2 & -1 \\ 1/2 & 1\end{bmatrix}\begin{bmatrix} v_{C\Sigma}^{\Sigma} \\ v_{C\Sigma}^{\Delta}\end{bmatrix}$$

$$\begin{bmatrix} m_{\Sigma} \\ m_{\Delta}\end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2\end{bmatrix}\begin{bmatrix} m_p \\ m_n\end{bmatrix} \quad\leftrightarrow\quad \begin{bmatrix} m_p \\ m_n\end{bmatrix} = \begin{bmatrix} 1/2 & -1 \\ 1/2 & 1\end{bmatrix}\begin{bmatrix} m_{\Sigma} \\ m_{\Delta}\end{bmatrix}$$

# DECOUPLED MODEL

$$
\frac{d}{dt}\begin{bmatrix}\mathbf{i}_{circ}\\ \mathbf{i}_g\\ \mathbf{v}_{C\Sigma}^{\Sigma}\\ \mathbf{v}_{C\Sigma}^{\Delta}\end{bmatrix}=\begin{bmatrix}-\frac{R_{br}}{L_{br}-Mbr}\mathbb{I}_3 & -\frac{R_{br}/2+R_g}{L_{br}+M_{br}+2L_g}\mathbb{I}_3 & \frac{(L_{br}+L_g)\mathbb{M}_p+(M_{br}+L_g)\mathbb{M}_n}{2(L_{br}-M_{br})(L_{br}+2L_g+M_{br})} & -\frac{(L_{br}+L_g)\mathbb{M}_p-(L_g+M_{br})\mathbb{M}_n}{(L_{br}-M_{br})(L_{br}+2L_g+M_{br})}\\ -\frac{R_{br}}{L_{br}-M_{br}}\mathbb{I}_3 & \frac{R_{br}/2+R_g}{L_{br}+2L_g+M_{br}}\mathbb{I}_3 & \frac{(L_{br}+L_g)\mathbb{M}_n+(L_g+M_{br})\mathbb{M}_p}{2(L_{br}-M_{br})(L_{br}+2L_g+M_{br})} & \frac{(L_{br}+L_g)\mathbb{M}_n-(L_g+M_{br})\mathbb{M}_p}{(L_{br}-M_{br})(L_{br}+2L_g+M_{br})}\\ \frac{1}{C_{br}}\mathbb{M}_p & \frac{1}{2C_{br}}\mathbb{M}_p & -\frac{1}{2C_{br}R_{esr}}\mathbb{I}_3 & \frac{1}{C_{br}R_{esr}}\mathbb{I}_3\\ \frac{1}{C_{br}}\mathbb{M}_n & -\frac{1}{2C_{br}}\mathbb{M}_n & -\frac{1}{2C_{br}R_{esr}}\mathbb{I}_3 & -\frac{1}{C_{br}R_{esr}}\mathbb{I}_3\end{bmatrix}\begin{bmatrix}\mathbf{i}_{circ}\\ \mathbf{i}_g\\ \mathbf{v}_{C\Sigma}^{\Sigma}\\ \mathbf{v}_{C\Sigma}^{\Delta}\end{bmatrix}+\begin{bmatrix}\frac{3}{4(L_{br}-M_{br})}\mathbb{I}_{3\times1} & -\frac{1}{2(L_{br}+2L_g+M_{br})}\mathbb{I}_3\\ \frac{1}{4(L_{br}-M_{br})}\mathbb{I}_{3\times1} & -\frac{3}{2(L_{br}+2L_g+M_{br})}\mathbb{I}_3\\ \mathbb{O}_{3\times1} & \mathbb{O}_3\\ \mathbb{O}_{3\times1} & \mathbb{O}_3\end{bmatrix}\begin{bmatrix}V_{dc}\\ \mathbf{v}_g+v_{CM}\mathbb{I}_{3\times1}\end{bmatrix}
$$




▲ Decoupled MMC model with main and secondary paths

# POWER EQUATIONS (I)

$$e_{p/n}(t) = \frac{V_{\mathrm{dc}}}{2} \mp \left(v_g(t) + v_{\mathrm{CM}}(t)\right) - \left(R_{\mathrm{br}} i_{p/n}(t) + L_{\mathrm{br}} \frac{\mathrm{d}}{\mathrm{d}t} i_{p/n}(t) - M_{\mathrm{br}} \frac{\mathrm{d}}{\mathrm{d}t} i_{n/p}(t)\right)$$

$$i_{p/n}(t) = \frac{I_{\mathrm{dc}}}{3} \pm \frac{i_g(t)}{2} + i_{\mathrm{circ}}(t)$$

where

| | |
|---|---|
| $V_{\mathrm{dc}}$ | the dc-link voltage |
| $v_g(t) = k_{\mathrm{ac}} \frac{V_{\mathrm{dc}}}{2} \cos\left(\omega t - \frac{2\pi(k-1)}{3}\right)$ | the ac grid voltage |
| $v_{\mathrm{CM}}(t) = \sum_i \hat{v}_{\mathrm{CM},i} \cos(i3\omega t)$ | the CM voltage |
| $I_{\mathrm{dc}}$ | the dc-link current |
| $i_g(t) = \hat{i}_g \cos\left(\omega t + \varphi - \frac{2\pi(k-1)}{3}\right)$ | the ac grid current |
| $i_{\mathrm{circ}}(t) = \sum_{6 \nmid l} \hat{i}_{\mathrm{circ},l} \cos\left(l2\omega t + \theta_l - \frac{2\pi(k-1)}{3}\right)$ | the circulating current |

with $k \in \{1, 2, 3\}$ the phase number.

# POWER EQUATIONS (II)

**Generic formulation** $p_{p/n}(t) = e_{p/n}(t) i_{p/n}(t)$

$$p_{p/n}(t) = \frac{V_{\mathrm{dc}} I_{\mathrm{dc}}}{6} \pm \frac{V_{\mathrm{dc}} i_g(t)}{4} + \frac{V_{\mathrm{dc}} i_{\mathrm{circ}}(t)}{2} \mp \frac{I_{\mathrm{dc}}\left(v_g(t) + v_{\mathrm{CM}}(t)\right)}{3} - \frac{i_g(t)\left(v_g(t) + v_{\mathrm{CM}}(t)\right)}{2} \mp i_{\mathrm{circ}}(t)\left(v_g(t) + v_{\mathrm{CM}}(t)\right) - \left(R_{\mathrm{br}} i_{p/n}(t)^2 + L_{\mathrm{br}} i_{p/n}(t)\frac{\mathrm{d}}{\mathrm{d}t} i_{p/n}(t) - M_{\mathrm{br}} i_{p/n}(t)\frac{\mathrm{d}}{\mathrm{d}t} i_{n/p}(t)\right)$$

**Transformation**

$$\begin{bmatrix} p_\Sigma \\ p_\Delta \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ -1/2 & 1/2 \end{bmatrix} \begin{bmatrix} p_p \\ p_n \end{bmatrix}$$

- $p_\Sigma$ only contains even harmonics
- $p_\Delta$ only contains odd harmonics

$$p_\Sigma(t) = \frac{V_{\mathrm{dc}} I_{\mathrm{dc}}}{3} + V_{\mathrm{dc}} i_{\mathrm{circ}}(t) - i_g(t)\left(v_g(t) + v_{\mathrm{CM}}(t)\right) - 2\left[R_{\mathrm{br}}\left(i_p(t)^2 + i_n(t)^2\right) + L_{\mathrm{br}}\left(i_p(t)\frac{\mathrm{d}}{\mathrm{d}t} i_p(t) + i_n(t)\frac{\mathrm{d}}{\mathrm{d}t} i_n(t)\right) - M_{\mathrm{br}}\left(i_p(t)\frac{\mathrm{d}}{\mathrm{d}t} i_n(t) + i_n(t)\frac{\mathrm{d}}{\mathrm{d}t} i_p(t)\right)\right]$$

$$p_\Delta(t) = -\frac{V_{\mathrm{dc}} i_g(t)}{8} + \frac{I_{\mathrm{dc}}\left(v_g(t) + v_{\mathrm{CM}}(t)\right)}{6} + \frac{i_{\mathrm{circ}}(t)\left(v_g(t) + v_{\mathrm{CM}}(t)\right)}{2}$$

**Reminder**

Zero net energy balance $\int_0^T p_\Sigma \mathrm{d}t = 0$

**Insight provided**

- Circulating current optimization (in steady state!)
- Converter energy requirement
- Converter safe operating area (a bit optimistic though)

# CIRCULATING CURRENT OPTIMIZATION (I)

- First discussed in [10].
- Without passives!

**W/o circulating current**

$$p_{\Sigma}(t) = \frac{I_{dc}V_{dc}}{3} - \hat{i}_g \cos(\omega t + \varphi) v_{CM}(t) - \frac{\hat{i}_g \hat{v}_g \cos(\varphi)}{2} - \frac{\hat{i}_g \hat{v}_g \cos(2\omega t + \varphi)}{2} + \underbrace{i_{circ}(t)}_{=0} V_{dc}$$

$$\Rightarrow I_{dc} = \frac{3\hat{i}_g \hat{v}_g \cos(\varphi)}{2V_{dc}}$$

**W/o common mode**

$$p_{\Sigma}(t) = \frac{V_{dc}I_{dc}}{3} + V_{dc} i_{circ}(t) - \frac{\hat{i}_g \hat{v}_g \cos(\varphi)}{2} - \frac{\hat{i}_g \hat{v}_g \cos(2\omega t + \varphi)}{2} = 0$$

$$\Rightarrow I_{dc} = \frac{3\hat{i}_g \hat{v}_g \cos(\varphi)}{2V_{dc}}$$

$$\Rightarrow i_{circ}(t) = \frac{\hat{i}_g \hat{v}_g \cos(2\omega t + \varphi)}{2V_{dc}}$$

**W/ common mode**

$$p_{\Sigma}(t) = -\hat{i}_g \cos(\omega t + \varphi) v_{CM}(t) - \frac{\hat{i}_g \hat{v}_g \cos(\varphi)}{2} - \frac{\hat{i}_g \hat{v}_g \cos(2\omega t + \varphi)}{2} + i_{circ}(t) V_{dc} + \frac{I_{dc}V_{dc}}{3} = 0$$

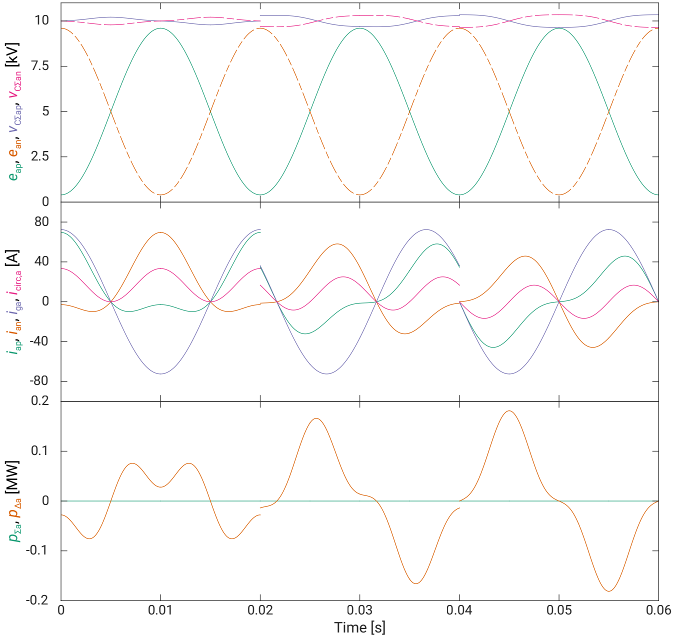
$$\Rightarrow I_{dc} = \frac{3\hat{i}_g \hat{v}_g \cos(\varphi)}{2V_{dc}}$$

$$\Rightarrow i_{circ}(t) = \frac{\hat{i}_g \left[2\cos(\omega t + \varphi) v_{CM}(t) + \hat{v}_g \cos(2\omega t + \varphi)\right]}{2V_{dc}}$$

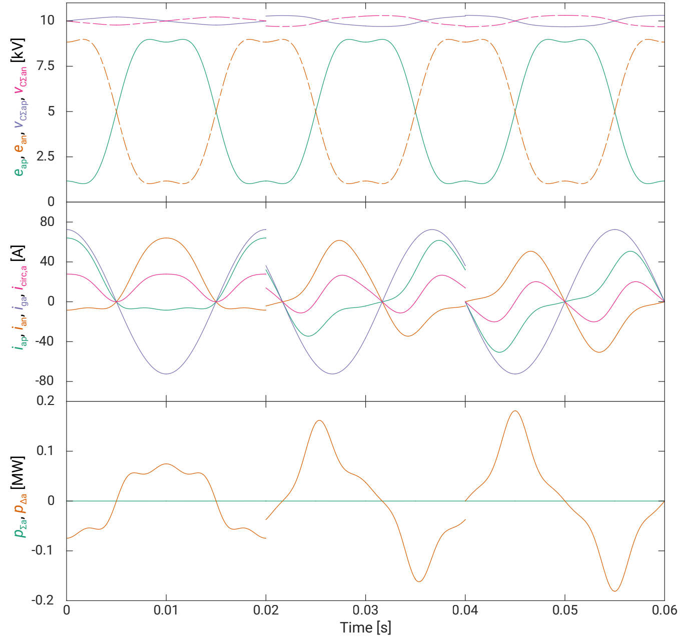
which means $2^{nd}$ and $4^{th}$ harmonics (at least!)

# CIRCULATING CURRENT OPTIMIZATION (II)

## W/o common mode




## W/ common mode



# BRANCH CAPACITANCE SELECTION

## Branch energy ripples

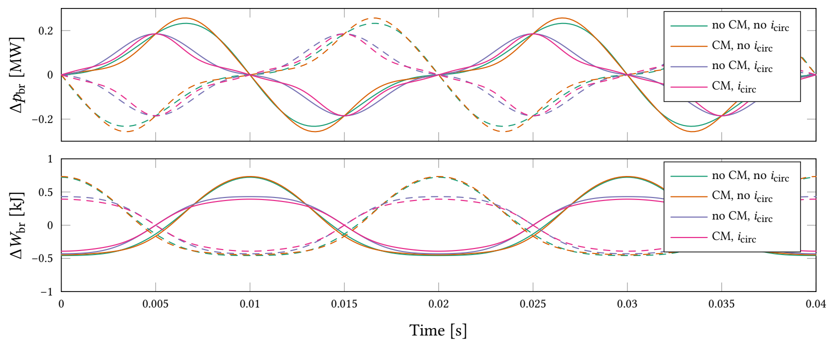
$$\Delta W_{\mathrm{br},+} = \frac{1}{2} C_{\mathrm{br}} v_{C\Sigma,\max}^{2} - \frac{1}{2} C_{\mathrm{br}} v_{C\Sigma 0}^{\star 2} \quad \rightarrow \quad C_{\mathrm{br}} = \frac{2\Delta W_{\mathrm{br},+}}{\left[(1+\varepsilon_{v_{C\Sigma}})^2 - 1\right] v_{C\Sigma 0}^{\star 2}}$$

$$\Delta W_{\mathrm{br},-} = \frac{1}{2} C_{\mathrm{br}} v_{C\Sigma 0}^{\star 2} - \frac{1}{2} C_{\mathrm{br}} v_{C\Sigma,\min} \quad \rightarrow \quad C_{\mathrm{br}} = \frac{2\Delta W_{\mathrm{br},-}}{\left[1 - (1-\varepsilon_{v_{C\Sigma}})^2\right] v_{C\Sigma 0}^{\star 2}}$$

## Energy requirement $k_{\mathrm{ac}} = 0.9$, $v_{C\Sigma 0}^{\star} = V_{\mathrm{dc}}$ and $\varepsilon_{v_{C\Sigma}} = 10\,\%$

| Case # | CM | 2nd (+ 4th) harmonic | Energy requirement [kJ/MVA] |
|---|---|---|---|
| 1 | ○ | ○ | 45.6 |
| 2 | ○ | ● | 46.3 |
| 3 | ● | ○ | 27.2 |
| 4 | ● | ● | 24.8 |

## Time domain waveforms $\varphi = -\pi/2$ (worst case)



# MMC CONTROL METHODS

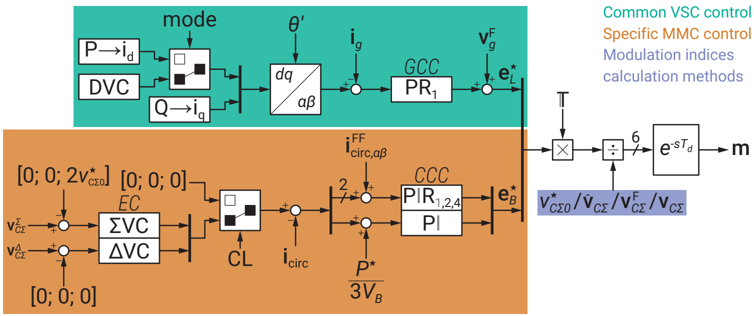
*Similarities and differences with other voltage source converters*

**Two modes of operation:**

1. Current source mode (also called inverter mode): transferring active power from the dc terminals to the ac terminals
2. Voltage source mode (also called rectifier mode): transferring active power from the ac terminals to the dc terminals

**Two sets of state variables:**

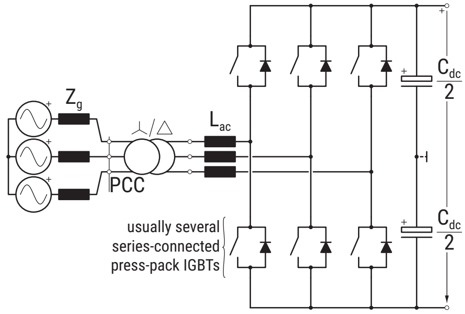
1. **External** state variables (dc-link voltage, grid currents, etc.): knowledge from VSC control is reused
2. **Internal** state variables (capacitor voltages, circulating currents): specific MMC control



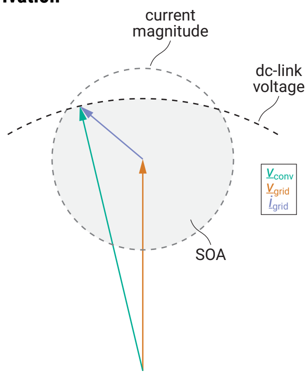

▲ Overall MMC control structure

## HVDC light

- 2-level or 3-level
- Series-connected StakPak IGBTs
- Low switching frequency (no multiplication factor since it is a macro switch)
- Large filters for grid code compliance

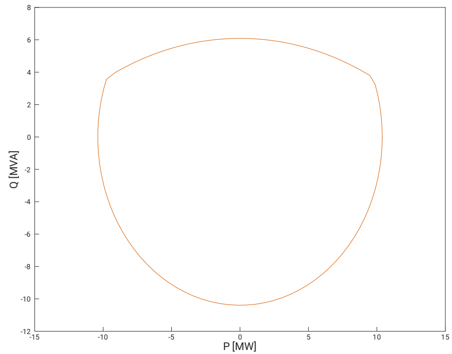



## SOA derivation




## P/Q diagram for the considered design

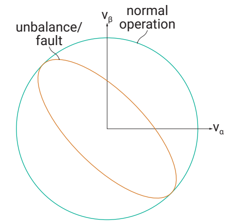
- $|V_{conv}| \leq V_{dc}/\sqrt{3}$ (CM injection)
- $I_{g,max} = 1$ kA (semi. devices)




Details about the control loops and their tuning can be found in: Amirnaser Yazdani and Reza Iravani. *Voltage-Sourced Converters in Power Systems:Modeling, Control, and Applications*. Wiley-IEEE Press, 2010

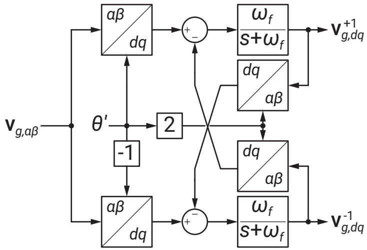
**Aim**

- Retrieve the positive and negative grid voltage sequences (in order to handle grid unbalances/faults)



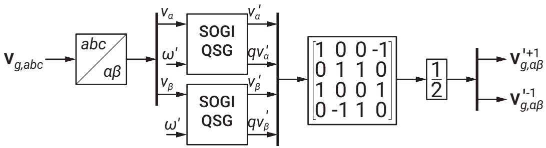

**Decoupled Double Synchronous Reference Frame (DDSRF)** [12]

- Implementation in *dq* frame
- LPF to remove oscillations at twice the frequency




**Double Second-Order Generalized Integrator (DSOGI)**

- Implementation in $\alpha\beta$ frame
- No additional filters required (with SOGI, LPF on $\alpha$ and notch on $\beta$)



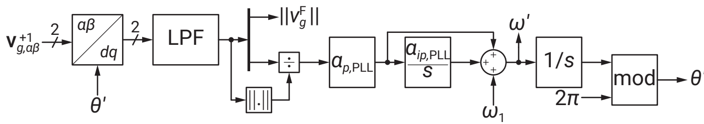
# COMMON CONTROL LOOPS WITH OTHER VSC'S: PHASE-LOCKED LOOP (PLL)

**Aim**

- Retrieve the grid frequency
- Retrieve the grid angle (esp. for control in *dq* frame)

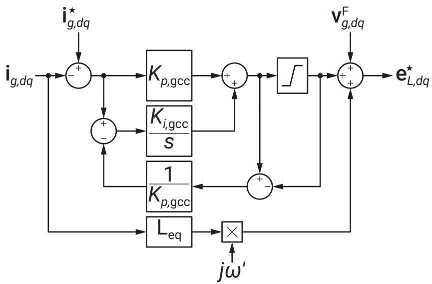
*dq* **PLL**

- Align with *d* axis by setting *q* component to 0
- Slow tuning to avoid instabilities



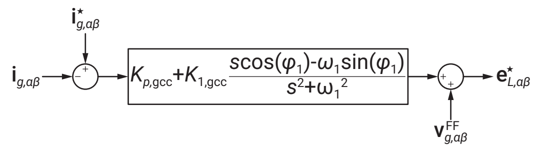
**PI in *dq* frame**

- Track dc components in a rotating reference frame
- Delay compensation by phase advance in the inverse Park transform



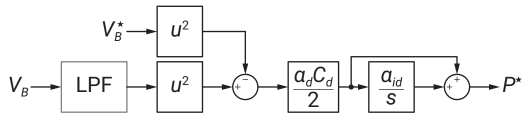

**PR in $\alpha\beta$ frame [13]**

- Track ac components in a stationary reference frame
- Delay compensation with $\varphi_h = h\omega_1 T_d$

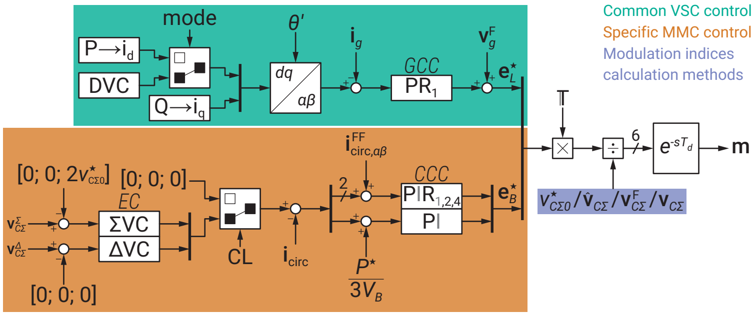


## Voltage control

- Based on the energy rather than the voltage information to be linear
- Sets the active power reference to the converter controlling the dc voltage
- Energy instead of voltage control in order to be linear




▲ DC voltage control



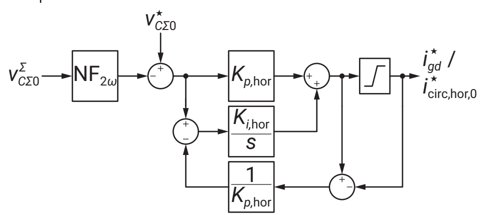

▲ Overall MMC control structure

# MMC SPECIFIC CONTROL LOOPS: ENERGY CONTROL (EC)

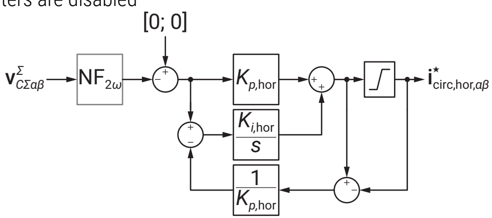
1. **Horizontal balancing**: shift energy between phase-legs using a CM current component
2. **Vertical balancing**: shift energy between branches using a fundamental ac current component

## Horizontal balancing

- Redistribution the CM component (i.e., the dc current for a dc/ac MMC) with the zero component

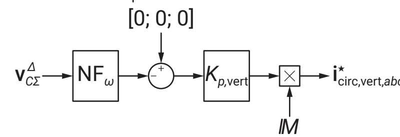



- Optimization of the capacitor voltage ripple with the $\alpha\beta$ components in case notch filters are disabled




## Vertical balancing

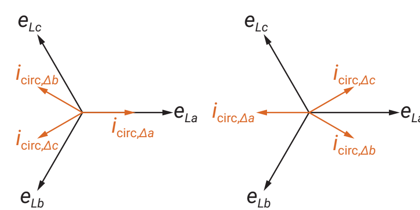
- Using a fundamental ac component




- Major contribution by [14] to cancel the circulating currents from vertical balancing at the dc terminals

$$\mathbb{M} = \begin{bmatrix} \cos(\theta_L) & \frac{-\sin(\theta_L)}{\sqrt{3}} & \frac{\sin(\theta_L)}{\sqrt{3}} \\ \frac{\sin(\theta_L - 2\pi/3)}{\sqrt{3}} & \cos(\theta_L - 2\pi/3) & \frac{-\sin(\theta_L - 2\pi/3)}{\sqrt{3}} \\ \frac{-\sin(\theta_L + 2\pi/3)}{\sqrt{3}} & \frac{\sin(\theta_L + 2\pi/3)}{\sqrt{3}} & \cos(\theta_L + 2\pi/3) \end{bmatrix}$$

where $\theta_L$ is the load current angle

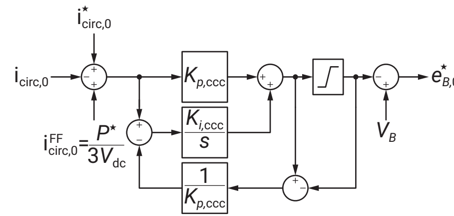


# MMC SPECIFIC CONTROL LOOPS: CIRCULATING CURRENT CONTROL (CCC)

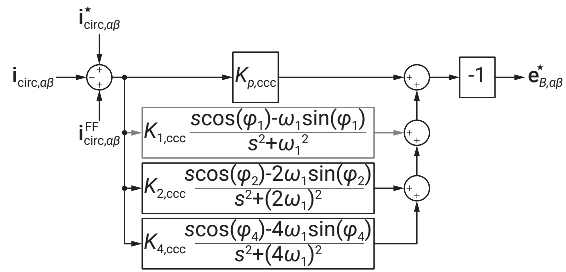
It has been shown in the power equations that the circulating current contains multiple low harmonic frequency components:

- **DC**: power exchange with the dc terminal, i.e., horizontal balancing
- **Fundamental AC**: vertical balancing
- **Second harmonic**: main component to be suppressed / controlled for capacitor voltage ripple reduction in steady-state
- **Fourth harmonic**: for capacitor voltage ripple reduction in steady-state with CM injection

PI and multiple R controllers are the best suited candidates to deal with these multiple harmonic components [15]




▲ Zero-sequence control



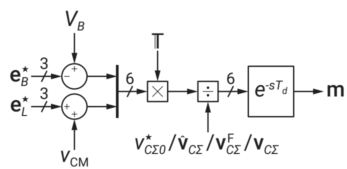

▲ $\alpha\beta$-sequence control

# MODULATION INDEX CALCULATION METHODS (I): DIRECT MODULATION

- The modulation indices are calculated from the *desired* dc average value
- The energy controllers **are disabled**
- The odd harmonics and integrator on dc component in the circulating current control **are disabled**
- Rely on self balancing of the branch energies [16]

$$\mathbf{m}_p = \frac{V_B/2 - \mathbf{e}_B^\star/2 - \mathbf{e}_L^\star}{v_{C\Sigma 0}^\star}$$

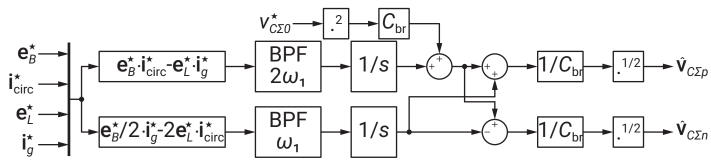
$$\mathbf{m}_n = \frac{V_B/2 - \mathbf{e}_B^\star/2 + \mathbf{e}_L^\star}{v_{C\Sigma 0}^\star}$$



# MODULATION INDEX CALCULATION METHODS (II): OPEN-LOOP CONTROL

- The modulation indices are calculated from *estimates* of the summed branch capacitors in steady-state [17]
- The energy controllers **are disabled**
- The odd harmonics and integrator on dc component in the circulating current control **are disabled**
- Self energy balance achieved [18]

$$
\begin{aligned}
m_p &= \frac{V_B/2 - e_B^\star/2 - e_L^\star}{\hat{v}_{C\Sigma p}} \\
m_n &= \frac{V_B/2 - e_B^\star/2 + e_L^\star}{\hat{v}_{C\Sigma n}}
\end{aligned}
$$

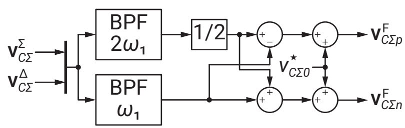


# MODULATION INDEX CALCULATION METHODS (III): HYBRID VOLTAGE CONTROL

- The modulation indices are calculated from *filtered values* of the summed branch capacitors measurements
- The energy controllers **are disabled**
- The odd harmonics and integrator on dc component in the circulating current control **are disabled**
- Self energy balance achieved [19]

$$\mathrm{m}_p = \frac{V_B/2 - \mathrm{e}_B^\star/2 - \mathrm{e}_L^\star}{\mathrm{v}_{C\Sigma p}^F}$$

$$\mathrm{m}_n = \frac{V_B/2 - \mathrm{e}_B^\star/2 + \mathrm{e}_L^\star}{\mathrm{v}_{C\Sigma n}^F}$$

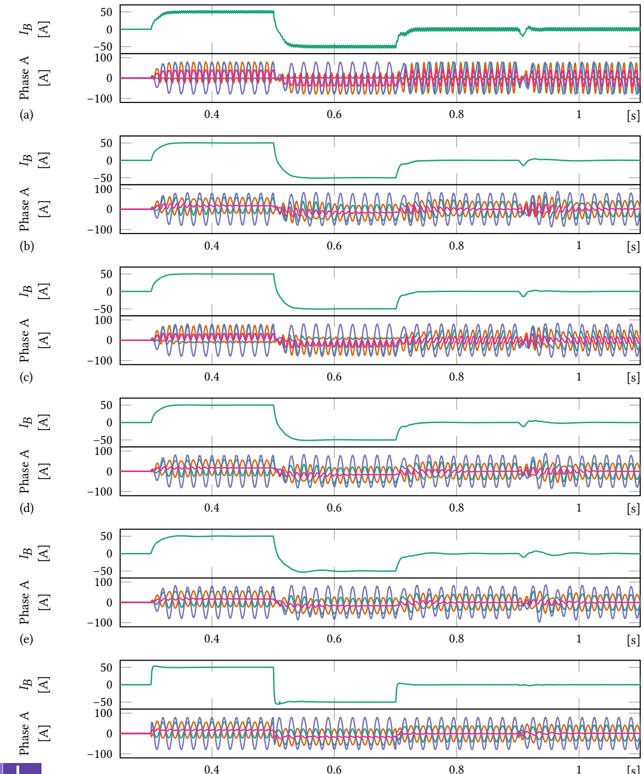


# MODULATION INDEX CALCULATION METHODS (IV): CLOSED-LOOP CONTROL

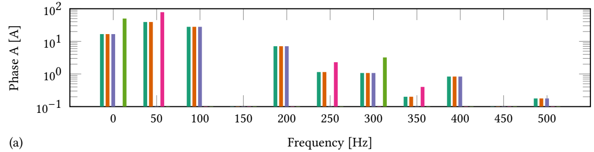
- The modulation indices are calculated from the *actual measurements* of the summed branch capacitors
- The energy controllers **are enabled**
- The odd harmonics in the circulating current control **are enabled**

This is by far the most complex control implementation, but at the same time the only method suitable for reaching the best dynamics.

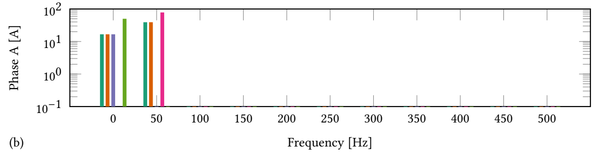
# CURRENTS IN INVERTER MODE



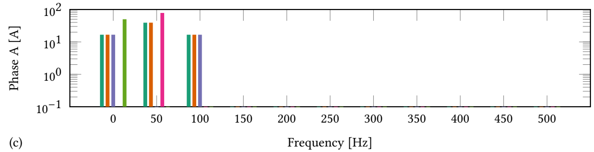

## No CCC



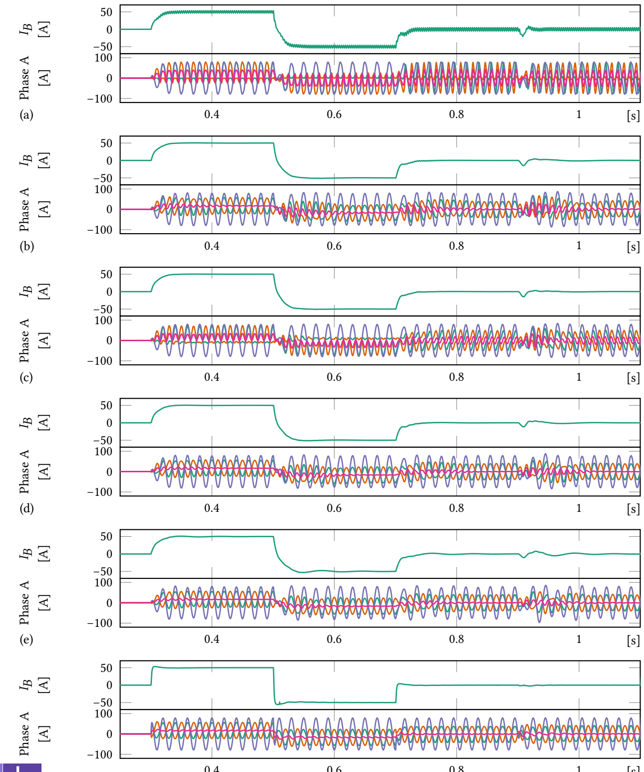

## CCSC / CCC dc circ



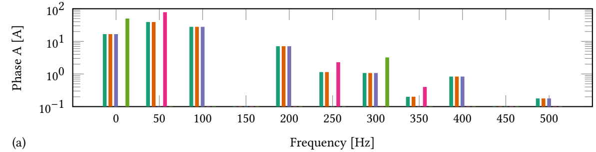

## CCSC / CCC + 2nd circ inj



# CURRENTS IN INVERTER MODE




## No CCC

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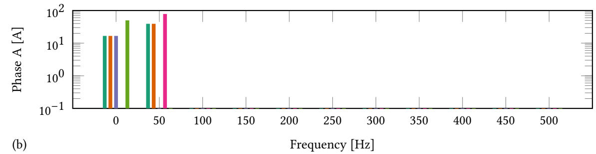
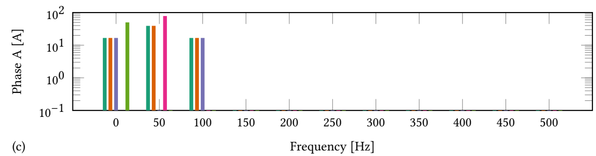
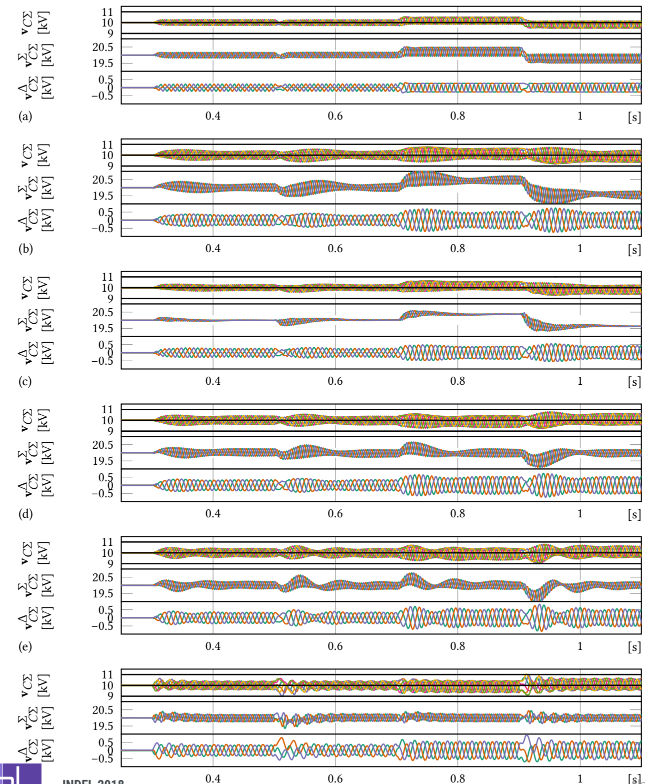



## CCSC / CCC + 2nd circ inj




⇒ CCSC / CCC **mandatory** to cancel low order harmonics

# SUMMED CAPACITOR VOLTAGES IN INVERTER MODE




**Few comments:**

- With the direct modulation, $\mathbf{v}^{\Sigma}_{C\Sigma}$ is not properly controller on reactive power steps (it settles to a value close to $V^{\star}_{C\Sigma 0}$)
- With the direct modulation w/o CCSC, the energies are shifted between the phase-legs (thanks to the uncontrolled circulating current) $\Rightarrow$ smallest capacitor voltage ripples are observed
- The self-balancing is more performant than the closed-loop energy balancing (it takes 3 fundamental periods to rebalance the voltages), however consequence is that $\mathbf{v}^{\Sigma}_{C\Sigma}$ dynamics are sluggish (increased voltage variation & lightly damped oscillatory response)
- BPFs tuning is affecting the performance of the hybrid voltage control method

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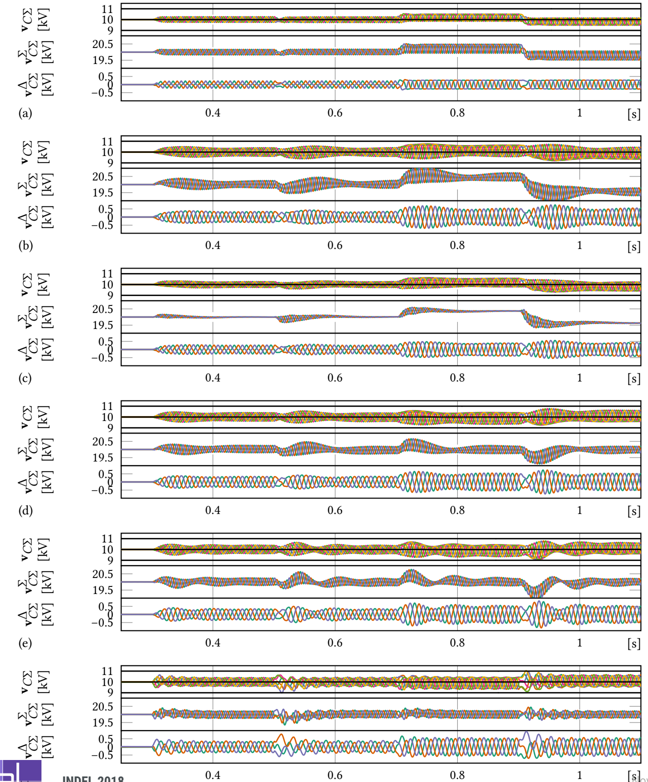


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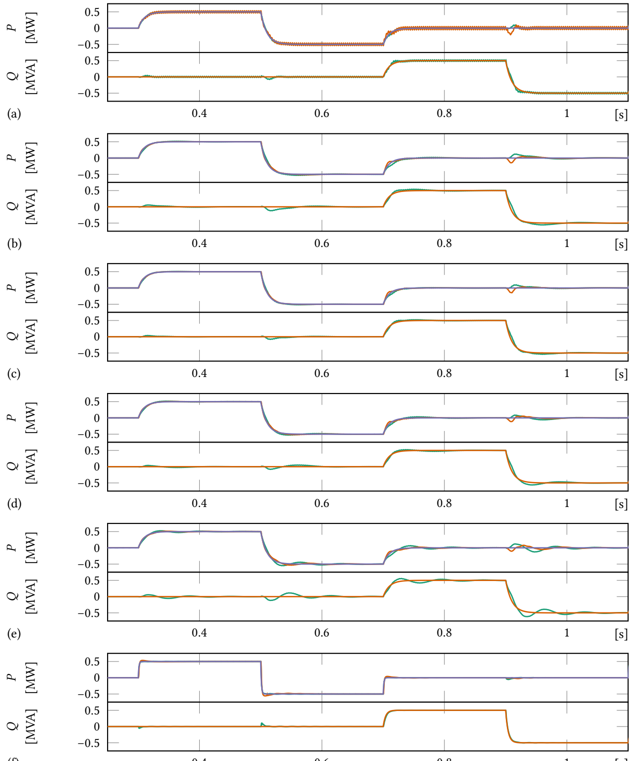
$\Rightarrow$ the branch energy control offers mitigated performances

# PQ TRACKING IN INVERTER MODE




**Few comments:**

- LPF filter bandwith 100 rad/s for self-balancing methods
- Low-order harmonics with direct modulation w/o CCSC
- Lightly damped oscillatory response with the hybrid voltage control method
- Dynamics are increased to 300 rad/s for the closed-loop control method without controller optimization
- Power decoupling is not perfect

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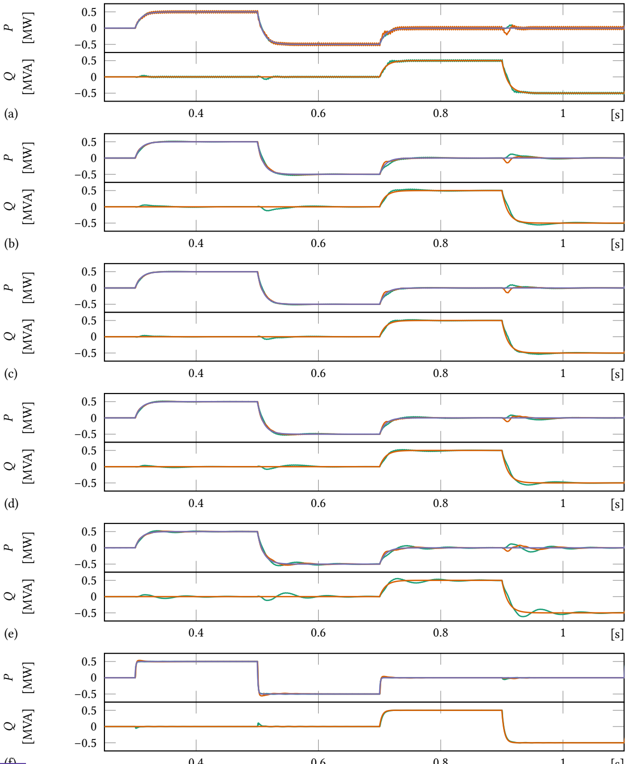


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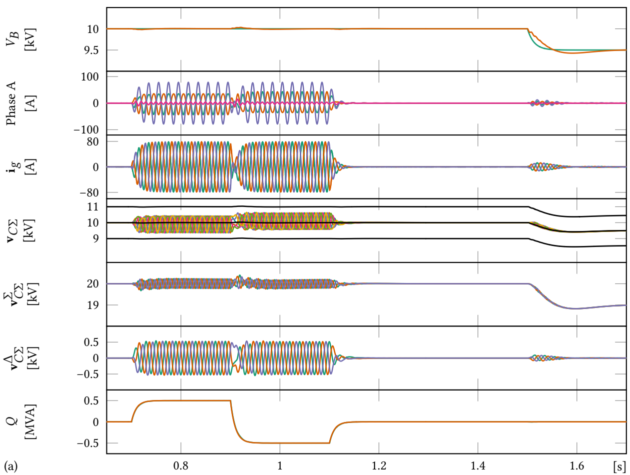
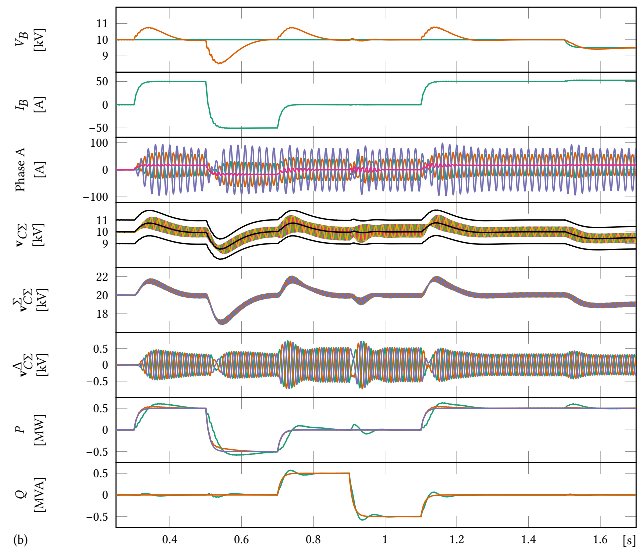
- Lightly damped oscillatory response with the hybrid voltage control method
- Dynamics are increased to 300 rad/s for the closed-loop control method without controller optimization
- Power decoupling is not perfect

⇒ clear advantage of the closed-loop control method for highly dynamic applications

## Open-circuit

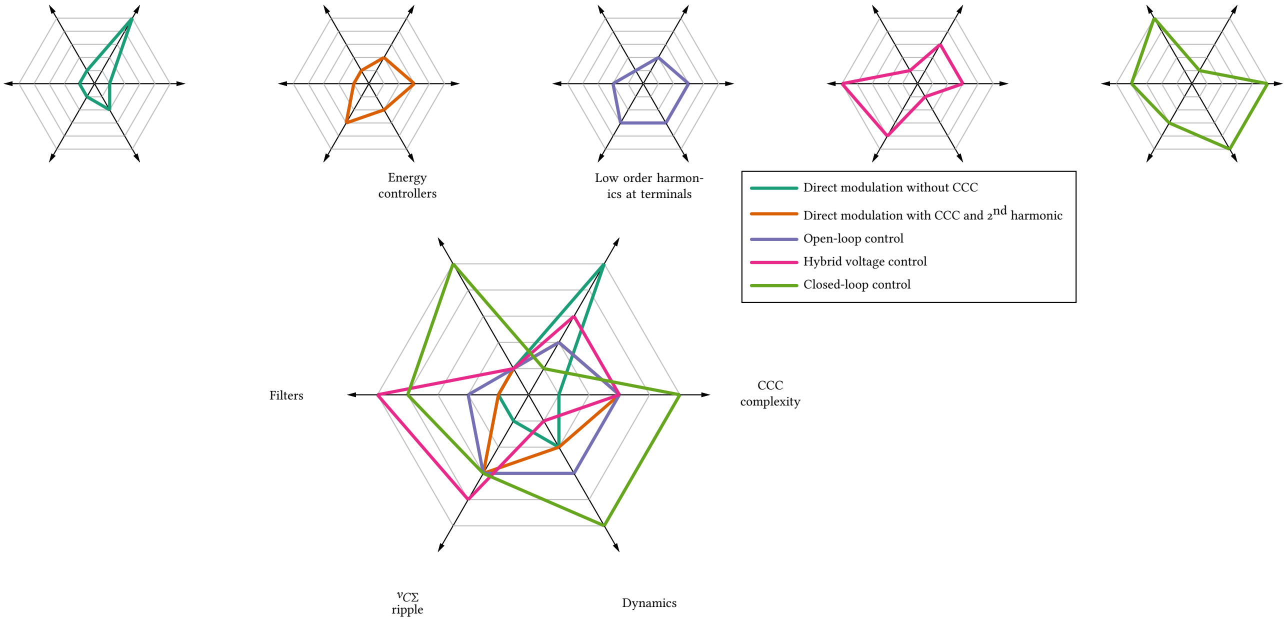



## Current source




- Circulating currents are canceling out at the terminals

# CONTROL METHOD PERFORMANCE RATING




⇒ the final choice depends on the application requirements / acceptable compromises between complexity and performance

# MMC MODULATION METHODS

*Variety of options are available...*

# CLASSIFICATION

- Choice and motivations for the choice completely different for an HVDC design compared to MVDC!

**Carrier-based**
- PS-PWM [20]
- LS-PWM (PD-PWM, etc.)
- SVM [21]

**Programmed**
- SHE [22]
- OPP [23], [24]

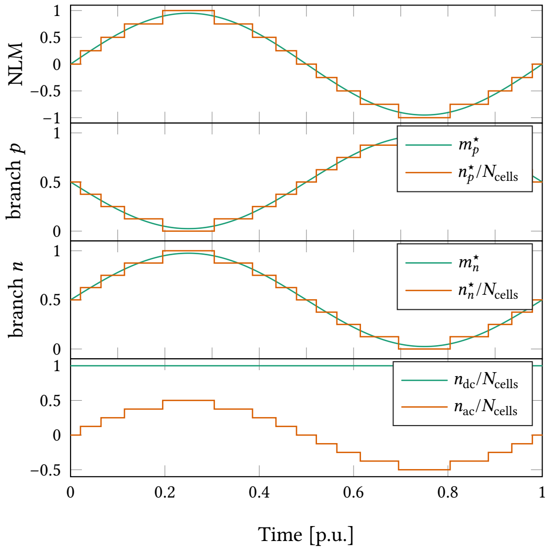
**Decision based**
- NLM
- FTB [25]

# NUMBER OF VOLTAGE LEVELS PER BRANCH

- Assuming no required action from circulating current control!
- Unipolar cells as base case

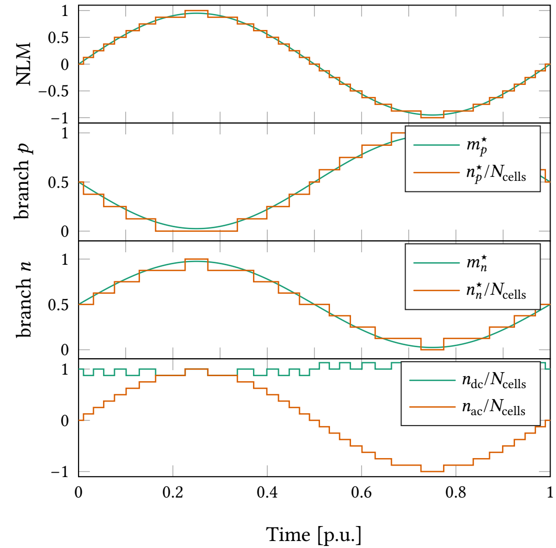
$N + 1$ **modulation**

- Synchronous switching of the branches within the same phase-leg




$2N + 1$ **modulation**

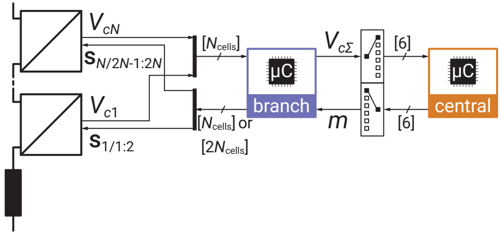
- Asynchronous switching of the branches within the same phase-leg



# MAXIMUM LEVEL OF CONTROL DECENTRALIZATION

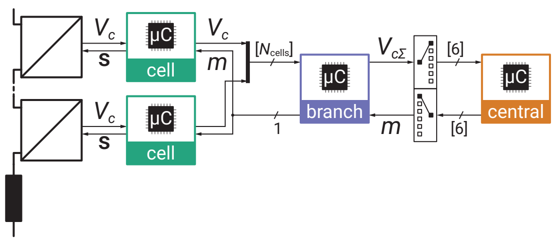
### Branch level modulation

- Each branch handled separately



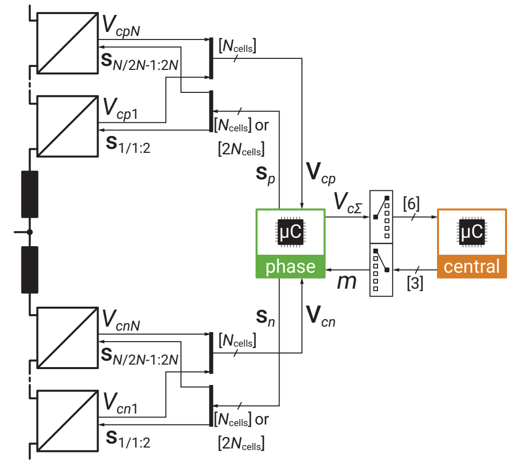

### Cell level modulation

- Each cell has its own modulator




### Phase-leg level modulation

- Aim at improving ac-side spectrum and unlocking full modulation method harmonic performance
- Compromises in the circulating current control
- SHE / OPP / SVM with $2N_{\text{cells}} + 1$ modulation



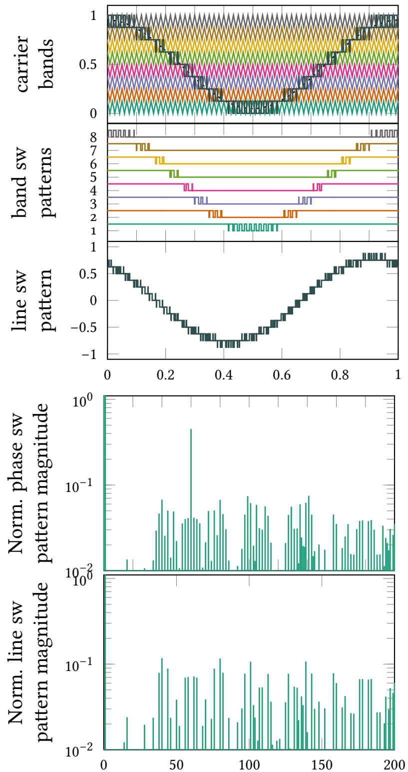

**Remark** µC denotes either a microcontroller, an FGPA, or a combination of both.

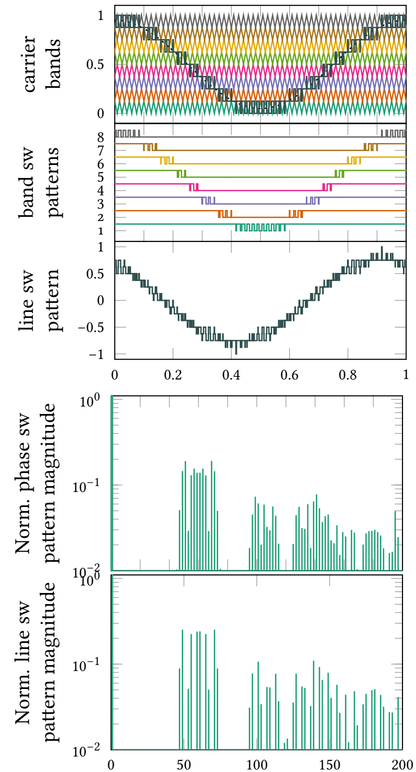
## PD-PWM

- Phase switching pattern with high harmonic at switching frequency
- Line switching pattern with low harmonic peak
- Lower THD

## APOD-PWM

- Phase switching pattern without strong harmonic at switching frequency
- Line switching pattern with distinctive carrier side bands
- Higher THD



# SINGLE-CARRIER PWM (I)

## Aim

- Reduce PWM computation requirement
- Flexibility of the modulator irrespectively of the number of cells or the LS-PWM type

## LS-PWM carriers

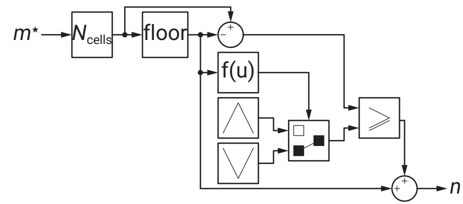
- Carrier band "height" determined by the number of cells
- Carrier phase determined by the modulation type
  - 0° phase-shift for PD-PWM
  - 180° phase-shift for neighboring carriers with APOD-PWM
  - 180° phase-shift for the upper half carriers with POD-PWM

## Background work

- Originally proposed in [26] for MMC with PD-PWM
- Detailed in [27] for FC with PD-PWM
- Extended and generalized for MMC in [8]

## Principle

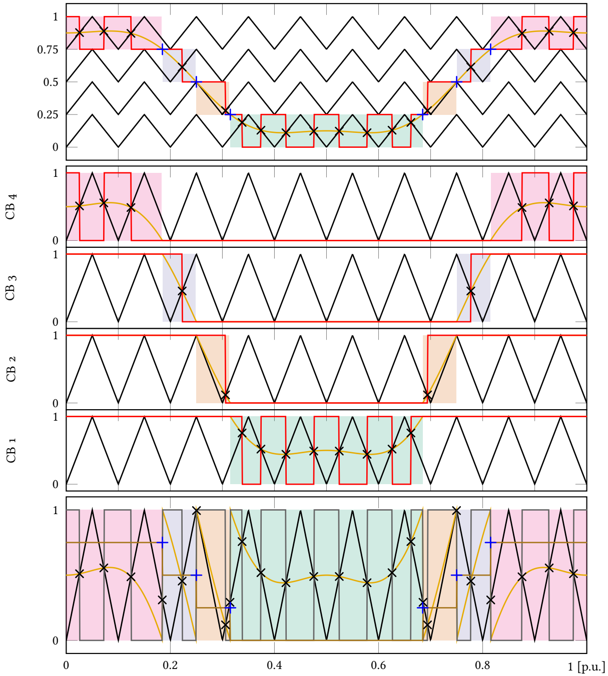
- Only the carrier where the reference belongs is active
- The *interesting* signal can be simply retrieved with the reminder from a floor function
- The *boring* signal is an offset called quantizer
- The level-shifted PWM method is obtained by selecting the right carrier with the function f(u)



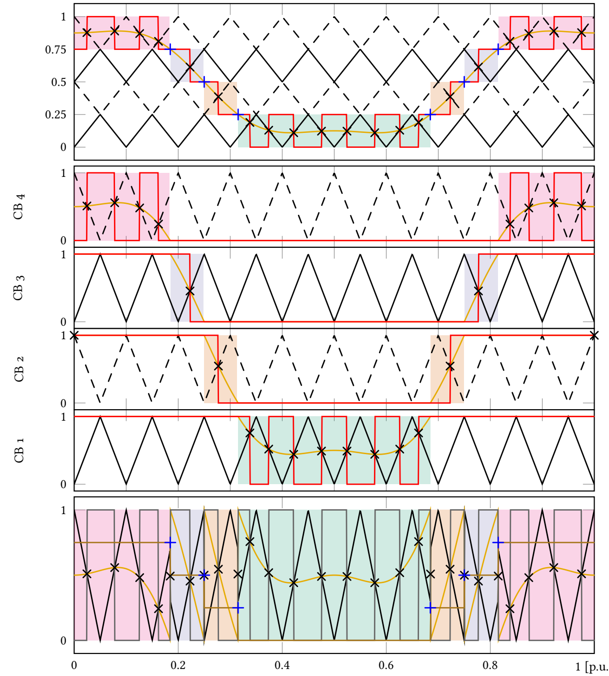

## Restriction

- Sorting algorithm and alike branch balancing schemes based on the instantaneous number of inserted cells per branch

# SINGLE-CARRIER PWM (II)



▲ PD-PWM example



▲ APOD-PWM example

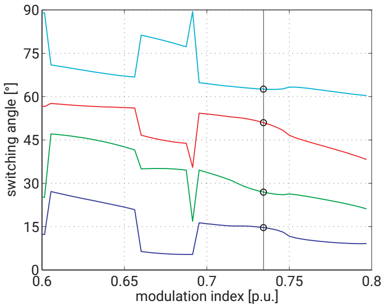
### Selective Harmonic Elimination

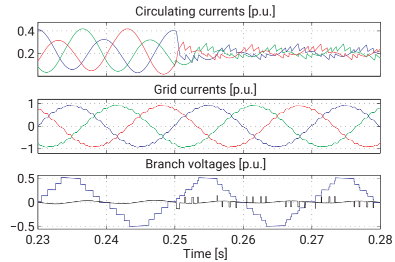
- Cancel one harmonic per switching angle plus 1 angle to set the modulation index over a quarter fundamental period
- Results in continuous switching angles ⇒ linear grid current controller
- $2N + 1$ modulation preferred when it comes to the circulating current control [28]

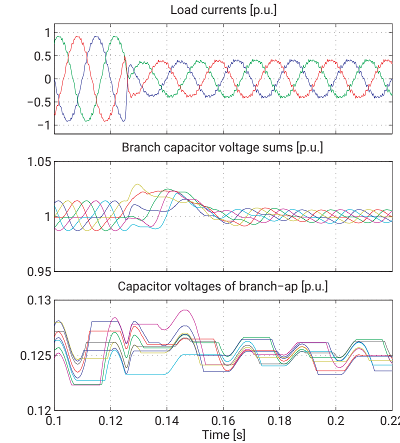
### Optimized Pulse Patterns

- Cancel low order harmonics and incorporate user settable constraints on individual harmonics for a given number of switching angles over a quarter fundamental period
- Results in discontinuous switching angles ⇒ non-linear grid current controller
- Different circulating current control methods for $N + 1$ and $2N + 1$ modulation [24]

### Results with OPPs from [24]



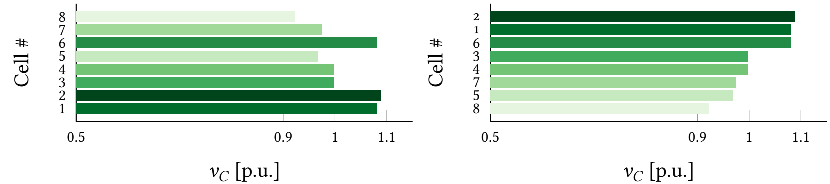




⇒ maximum performance without compromising the switching frequency

# SORTING ALGORITHMS

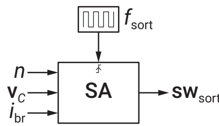
## Principle

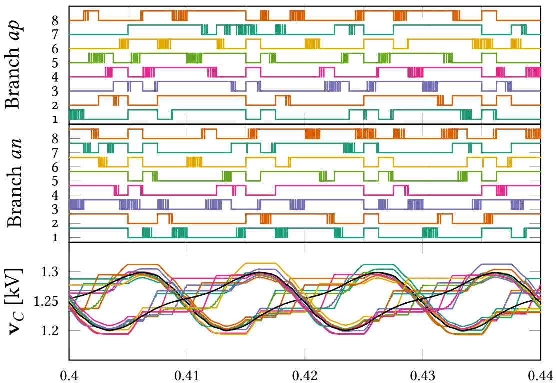
- Depending on the branch current polarity (and switching state), the inserted cells are either charged or discharged




## Simple sorting

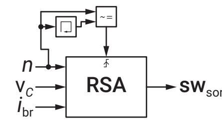
- The sorting algorithm is triggered at $f_{sort}$
- All switching signals can be modified

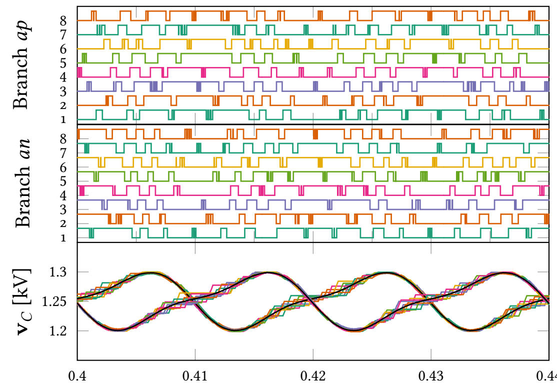



## Restricted sorting [29]

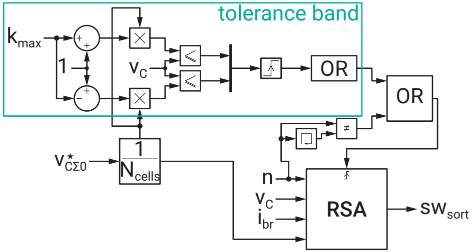
- The sorting algorithm is triggered when a switching transition occur
- No additional switching events!



## Tolerance band [25]

- With very low switching frequency, the restricted algorithm cannot maintain the cell capacitor voltages within their limits
- Another condition forces the swapping of two cells when the bands are exceeded




▲ Restricted Sorting Algorithm with tolerance band

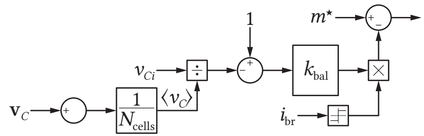
# CELL BALANCING WITH DISTRIBUTED MODULATORS

## Principle

- The proportional control action cancel out at the branch level

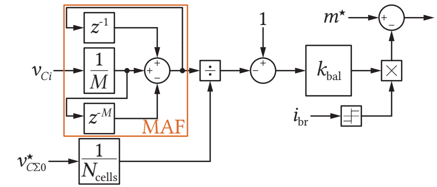
## Branch average based

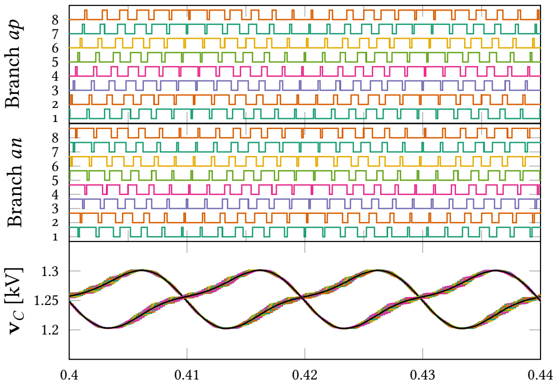
- The *instantaneous* summed branch capacitor average is sent by the branch controller [20]

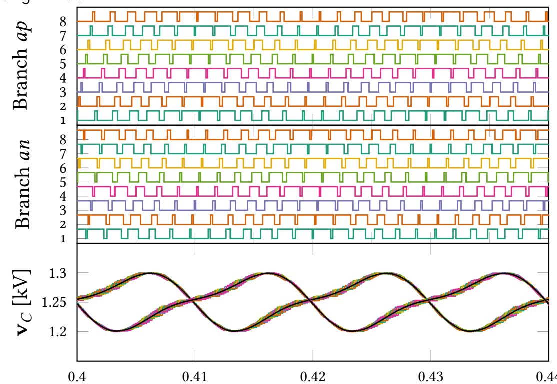



## Moving average filter based

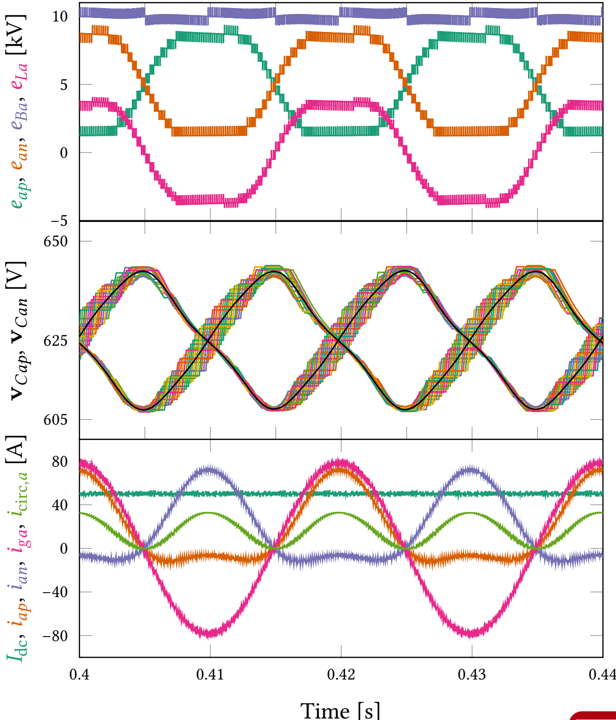
- The summed branch capacitor average is retrieved by a moving average filter with a long window



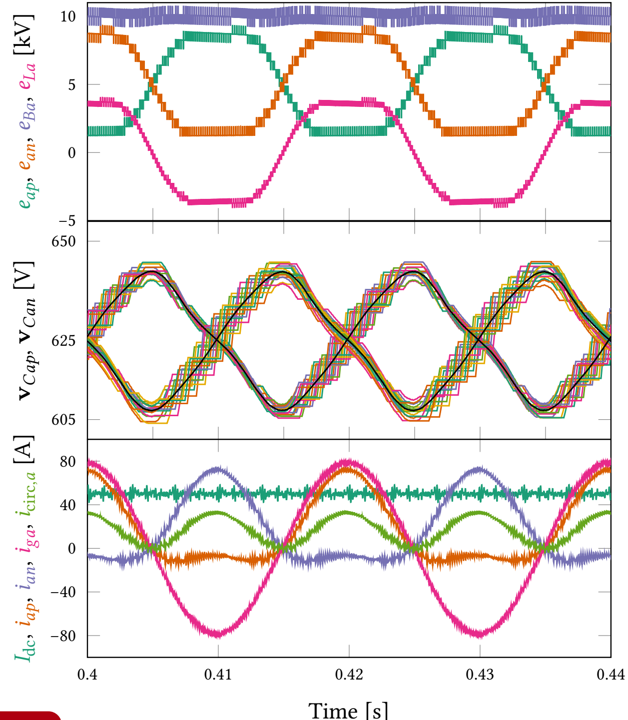



**Enhanced restricted sorting algorithm** ($N+1$)




**PS-PWM with moving average filter** ($2N+1$)




$\overline{f_{\mathrm{sw,cell}}} = 375\,\mathrm{Hz}$

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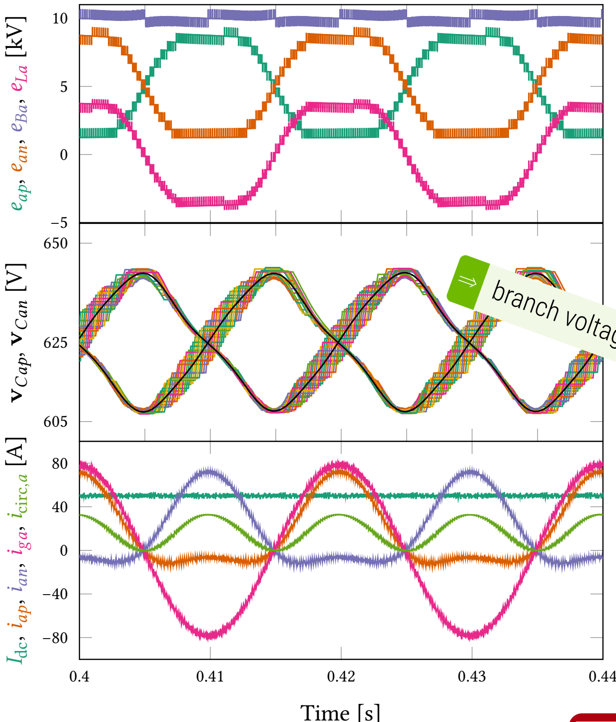


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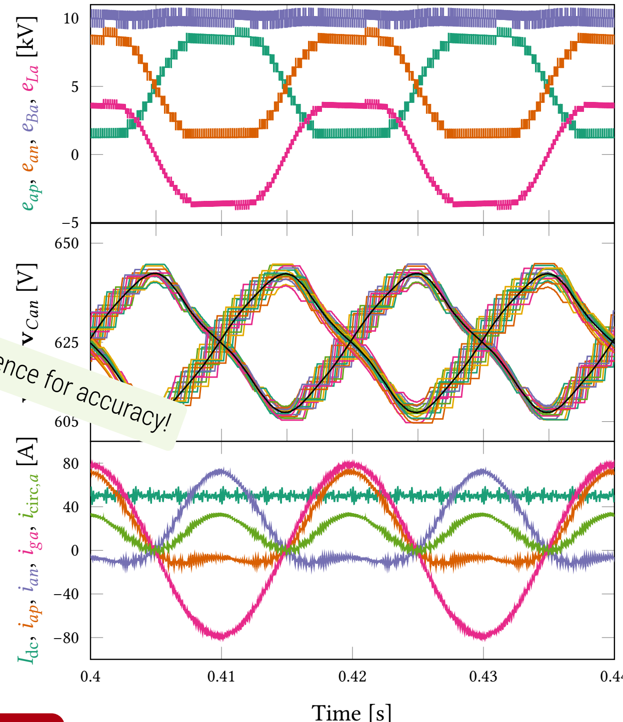



⇒ branch voltage reference for accuracy!

$\overline{f_{\text{sw,cell}}} = 375\,\text{Hz}$

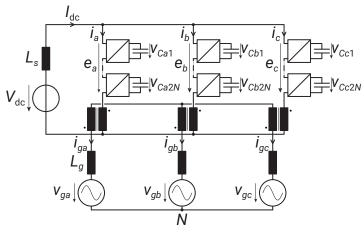
# GALVANICALLY ISOLATED MODULAR CONVERTER

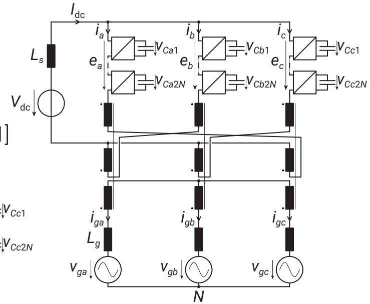
*Interleaved and Stacked variants*

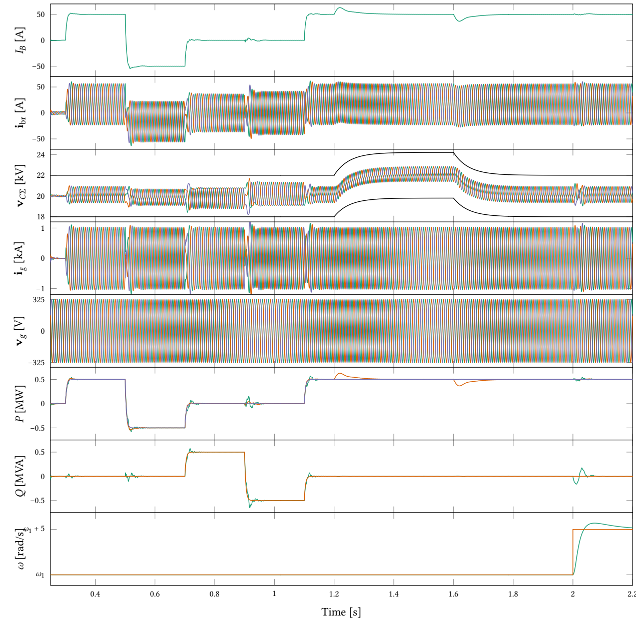
# TRANSFORMER INTEGRATION PROPOSALS IN THE LITERATURE

**Open End Winding MMC** [30]

- Only **one** branch per phase-leg
- No CM voltage injection
- No current decoupling
- DC bias in trafo → zig-zag trafo [31]

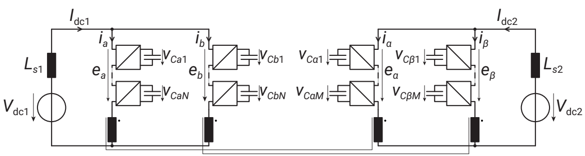







**Isolated dc/dc converter** [32]

- DC bias cancellation for any operating point
- Two-phase at least



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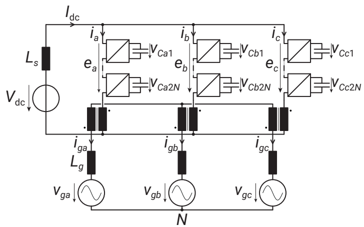
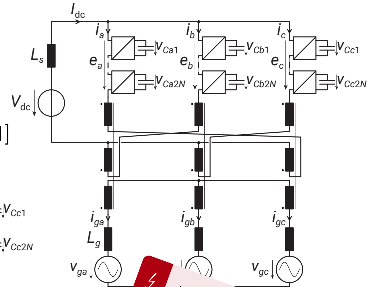
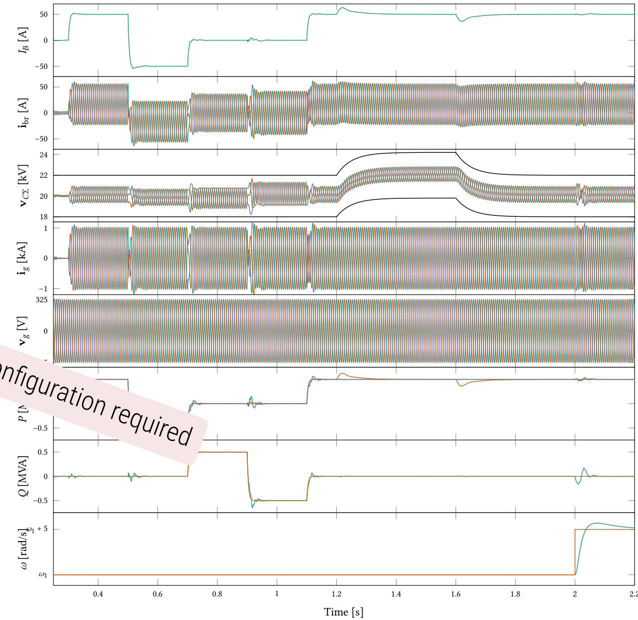


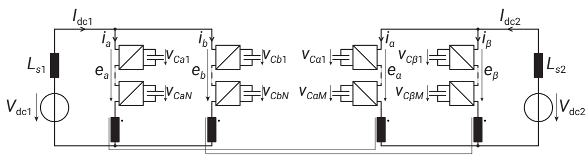




proper transformer configuration required

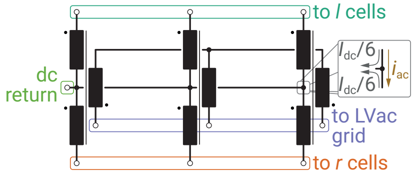
**Isolated dc/dc converter** [32]

- DC bias cancellation for any operating point
- Two-phase at least



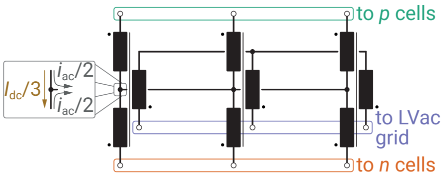
# THE GALVANICALLY ISOLATED MODULAR CONVERTER

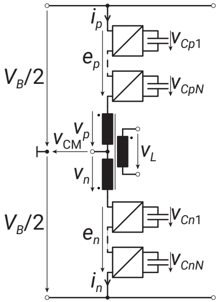
- Multi-windings trafo
- Unification of proposals [33] & [34]
- Dc bias cancellation is effective for any operating point
- Different dc voltage levels can be accommodated with the same branch design

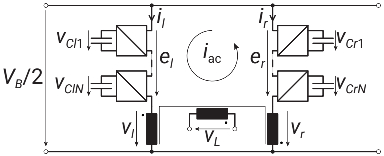



▲ iGIMC trafo

▼ sGIMC trafo



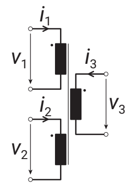



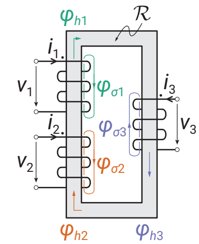

▲ Interleaved GIMC (iGIMC)

◀ Stacked GIMC (sGIMC)

### Method

- Carried out once via terminal mapping
- $\mathbf{v} = \mathbb{L}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i} + \mathbb{R}\mathbf{i}$




$$\mathbb{L} = \begin{bmatrix} L_{\sigma,\mathrm{HV}} + L_{\mathrm{HV}} & L_{\mathrm{HV}} & M_{\mathrm{LV}} \\ L_{\mathrm{HV}} & L_{\sigma,\mathrm{HV}} + L_{\mathrm{HV}} & M_{\mathrm{LV}} \\ M_{\mathrm{LV}} & M_{\mathrm{LV}} & L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}} \end{bmatrix}$$

$$\mathbb{R} = \begin{bmatrix} R_{\mathrm{HV}} & 0 & 0 \\ 0 & R_{\mathrm{HV}} & 0 \\ 0 & 0 & R_{\mathrm{LV}} \end{bmatrix}$$

### iGIMC

$$v_1 = v_l \qquad i_1 = i_l$$
$$v_2 = -v_r \qquad i_2 = -i_r$$
$$v_3 = v_L \qquad i_3 = -i_g$$

Result:

$$v_B = e_l + e_r + R_{\mathrm{HV}}\left(i_l + i_r\right) + L_{\sigma,\mathrm{HV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_l + \frac{\mathrm{d}}{\mathrm{d}t}i_r\right)$$

$$0 = -e_l + e_r + R_{\mathrm{HV}}\left(-i_l + i_r\right) + \left(L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}}\right)\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_l + \frac{\mathrm{d}}{\mathrm{d}t}i_r\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{\mathrm{CM}}$$

$$v_L = M_{\mathrm{LV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_l - \frac{\mathrm{d}}{\mathrm{d}t}i_r\right) - \left(L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}}\right)\frac{\mathrm{d}}{\mathrm{d}t}i_g - R_{\mathrm{LV}}i_g$$

### sGIMC

$$v_1 = v_p \qquad i_1 = i_p$$
$$v_2 = -v_n \qquad i_2 = -i_n$$
$$v_3 = v_L \qquad i_3 = -i_g$$

Result:

$$v_B = e_p + e_n + R_{\mathrm{HV}}\left(i_p + i_n\right) + L_{\sigma,\mathrm{HV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right)$$

$$0 = -e_p + e_n + R_{\mathrm{HV}}\left(-i_p + i_n\right) + \left(L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}}\right)\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{MO}$$

$$v_L = M_{\mathrm{LV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_p - \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) - \left(L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}}\right)\frac{\mathrm{d}}{\mathrm{d}t}i_g - R_{\mathrm{LV}}i_g$$

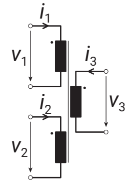
# GIMC MODELING

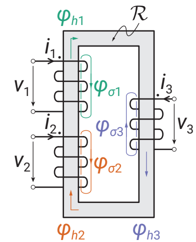
## Method

- Carried out once via terminal mapping
- $\mathbf{v} = \mathbb{L}\frac{\mathrm{d}}{\mathrm{d}t}\mathbf{i} + \mathbb{R}\mathbf{i}$

$$\mathbb{L} = \begin{bmatrix} L_{\sigma,\mathrm{HV}} + L_{\mathrm{HV}} & L_{\mathrm{HV}} & M_{\mathrm{LV}} \\ L_{\mathrm{HV}} & L_{\sigma,\mathrm{HV}} + L_{\mathrm{HV}} & M_{\mathrm{LV}} \\ M_{\mathrm{LV}} & M_{\mathrm{LV}} & L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}} \end{bmatrix}$$

$$\mathbb{R} = \begin{bmatrix} R_{\mathrm{HV}} & 0 & 0 \\ 0 & R_{\mathrm{HV}} & 0 \\ 0 & 0 & R_{\mathrm{LV}} \end{bmatrix}$$




⇒ same as for conventional MMC

### iGIMC

$$v_1 = v_l \qquad i_1 = i_l$$
$$v_2 = -v_r \qquad i_2 = -i_r$$
$$v_3 = v_L \qquad i_3 = -i_g$$

Result:

$$v_B = e_l + e_r + R_{\mathrm{HV}}(i_l + i_r) + L_{\sigma,\mathrm{HV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_l + \frac{\mathrm{d}}{\mathrm{d}t}i_r\right)$$

$$0 = -e_l + e_r + R_{\mathrm{HV}}(-i_l + i_r) + (L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}})\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_l + \frac{\mathrm{d}}{\mathrm{d}t}i_r\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{\mathrm{CM}}$$

$$v_L = M_{\mathrm{LV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_l - \frac{\mathrm{d}}{\mathrm{d}t}i_r\right) - (L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}})\frac{\mathrm{d}}{\mathrm{d}t}i_g - R_{\mathrm{LV}}i_g$$

### sGIMC

$$v_1 = v_p \qquad i_1 = i_p$$
$$v_2 = -v_n \qquad i_2 = -i_n$$
$$v_3 = v_L \qquad i_3 = -i_g$$

Result:

$$v_B = e_p + e_n + R_{\mathrm{HV}}(i_p + i_n) + L_{\sigma,\mathrm{HV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right)$$

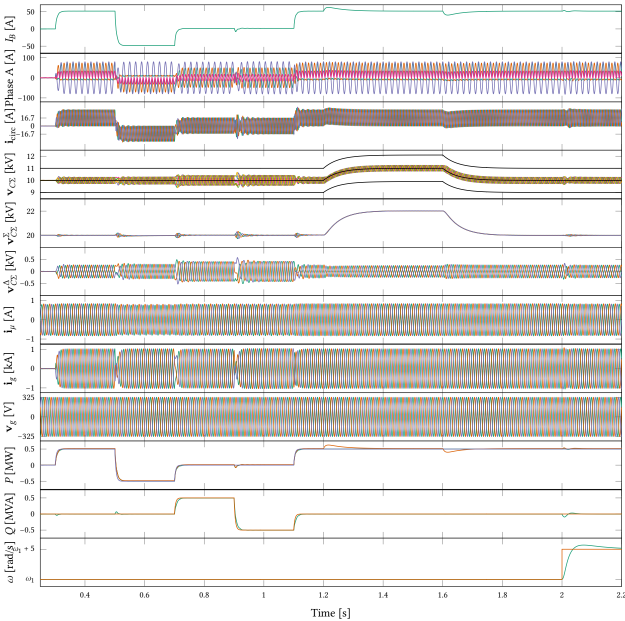
$$0 = -e_p + e_n + R_{\mathrm{HV}}(-i_p + i_n) + (L_{\sigma,\mathrm{HV}} + 2L_{\mathrm{HV}})\left(-\frac{\mathrm{d}}{\mathrm{d}t}i_p + \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) + 2M_{\mathrm{LV}}\frac{\mathrm{d}}{\mathrm{d}t}i_g - 2v_{MO}$$

$$v_L = M_{\mathrm{LV}}\left(\frac{\mathrm{d}}{\mathrm{d}t}i_p - \frac{\mathrm{d}}{\mathrm{d}t}i_n\right) - (L_{\sigma,\mathrm{LV}} + L_{\mathrm{LV}})\frac{\mathrm{d}}{\mathrm{d}t}i_g - R_{\mathrm{LV}}i_g$$

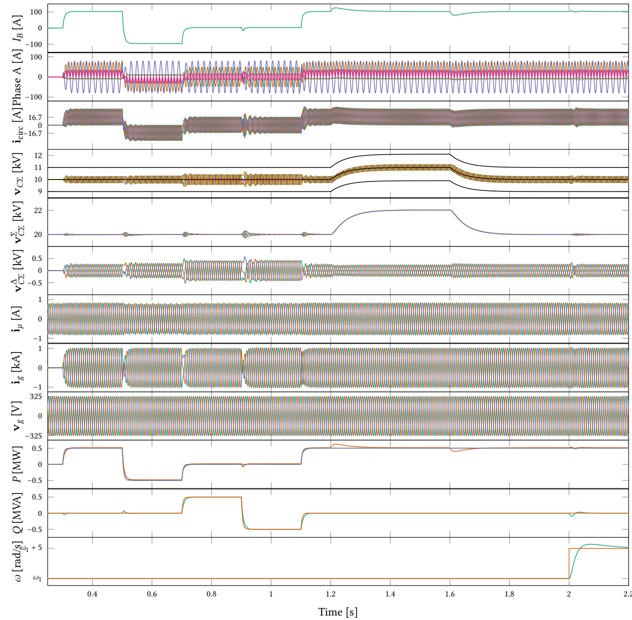
# GIMC OPERATION

- **Inverter** mode operation

  - sGIMC

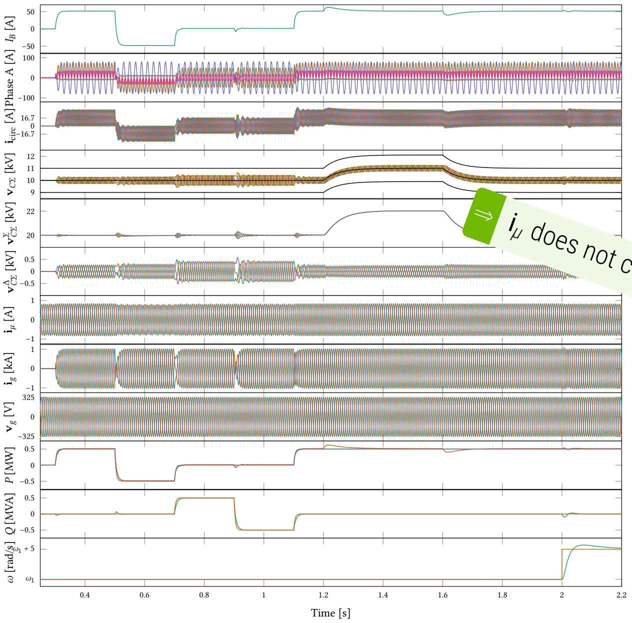



  - iGIMC

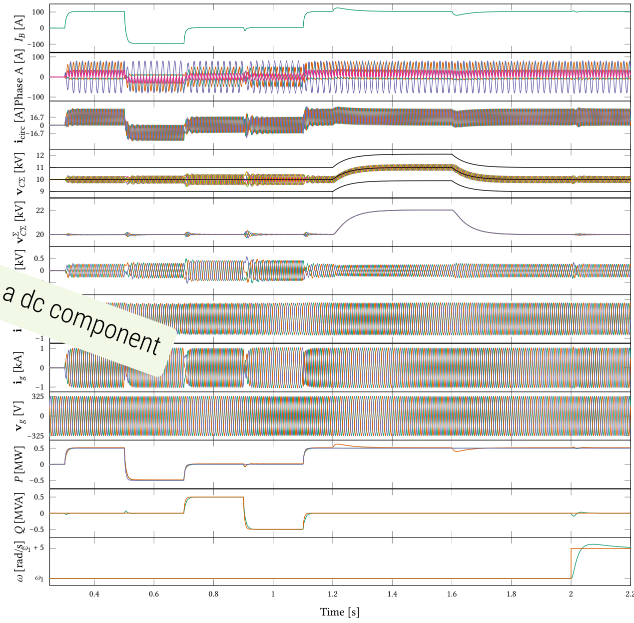


- **Inverter** mode operation

▼ sGIMC



▼ iGIMC



⇒ $\mathbf{i}_\mu$ does not contain a dc component

# MAGNETIC COMPONENTS DESIGN

*How much gain with the integrated magnetic component?*

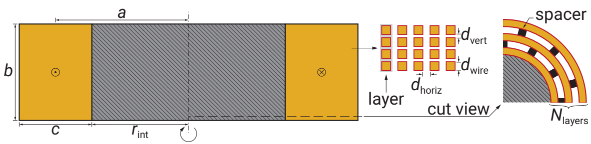
# AIR-CORE BRANCH INDUCTOR SIZING

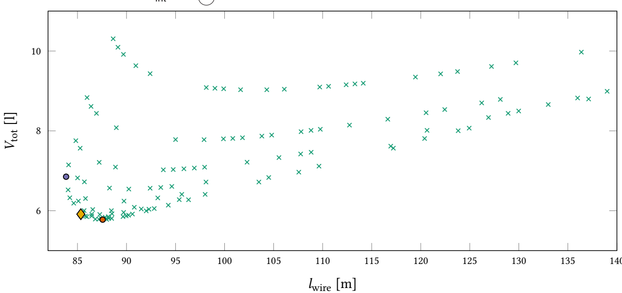
## Design space

- Target: $L_{br} = 2.5\,\text{mH}$
- $i_{br,rms} = 56.7\,\text{A}$
- $J = 2\,\text{A/mm}^2$

## Analytical designs

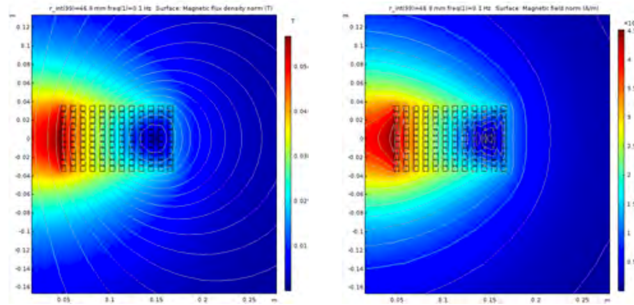
- $L_{Welsby} = \dfrac{\mu_0 N^2 \pi a^2}{b} \dfrac{1}{1 + 0.9\frac{a}{b} + 0.32\frac{c}{a} + 0.84\frac{c}{b}}$ [H]
- Cost function: $J_{cost} = \sqrt{\left(\dfrac{l_{wire}}{10}\right)^2 + V_{tot}^2}$



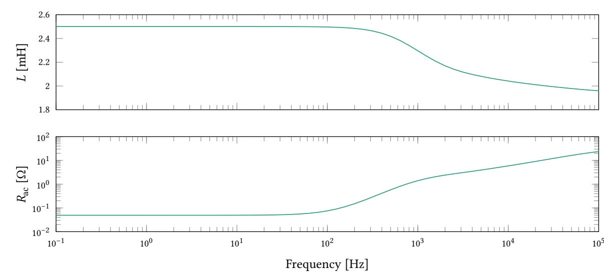

## Optimal design

- $N_{turns} = 132$, $N_{layers} = 12$, $r_{int} = 42.4\,\text{mm} \xrightarrow{\text{FEM opt}} 42.6\,\text{mm}$
- $V_{tot} \approx 6\,\text{l}$
- $P_{losses} = 130\,\text{W}$



▲ COMSOL frequency analysis @ 0.1 Hz (← B-field / → H-field)

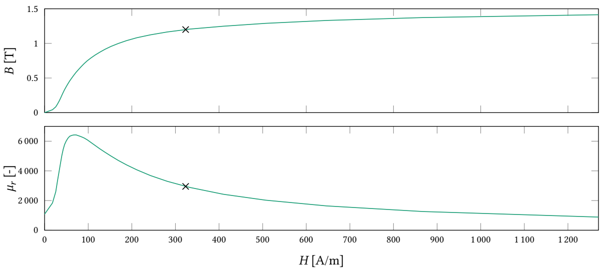
▼ Impedance between 0.1 Hz and 100 kHz

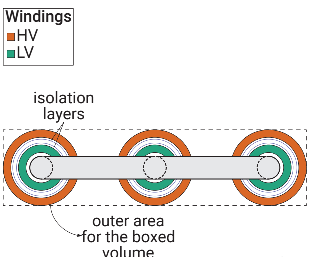


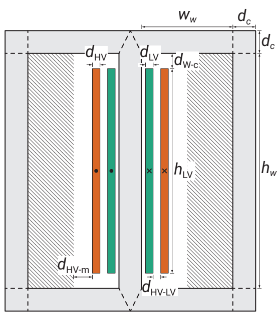
# LFT DESIGN

## Design

- Three-limb dry-type transformer
- Short-circuit impedance > 5 %
- Silicon steel (M19 from AK Steel): $B_{\max} = 1.2\,\mathrm{T} \Rightarrow i_\mu = 1.37\,\%$
- $V_{\mathrm{t2t}} = 10\,\mathrm{V}$
- $J_{\mathrm{HV}} = 2.5\,\mathrm{A/mm^2}$, $J_{\mathrm{LV}} = 2\,\mathrm{A/mm^2}$



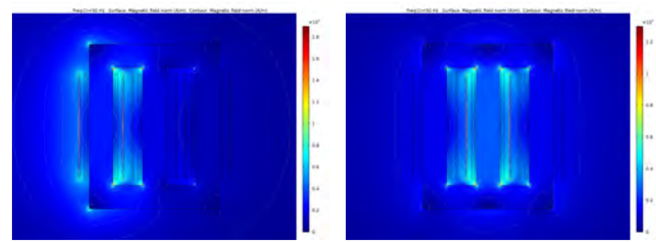

▲ top view
▸ side view

## Core's permeance model

- Single unknown: $w_w = \dfrac{4\mu_0\mu_r A_c - \mathcal{P}_c^\star(6+\pi)d_c}{(4+6a)\mathcal{P}_c^\star}$

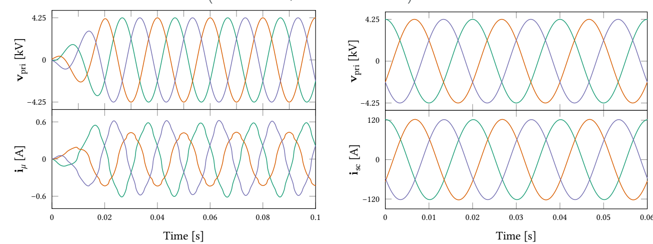
## Best design

- $w_w = 214.4\,\mathrm{mm}$ and $a = 4$
- $V_{\mathrm{tot}} = 481.7\,\mathrm{l}$
- $P_{w,\mathrm{HV}} = 79.08\,\mathrm{W}$ and $P_{w,\mathrm{LV}} = 30.93\,\mathrm{W}$ per phase



▲ Leakage H-field in COMSOL @ 50 Hz (← phase *a* / → phase *b*)

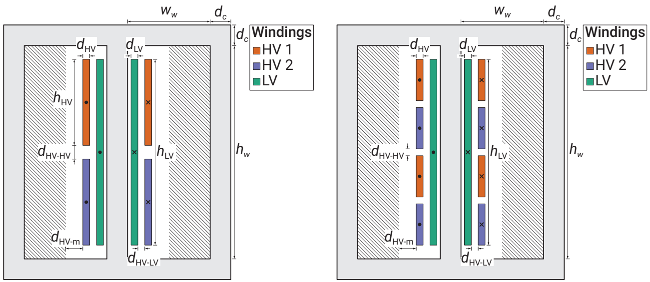
▼ Time domain simulations (← no-load / → short-circuit)



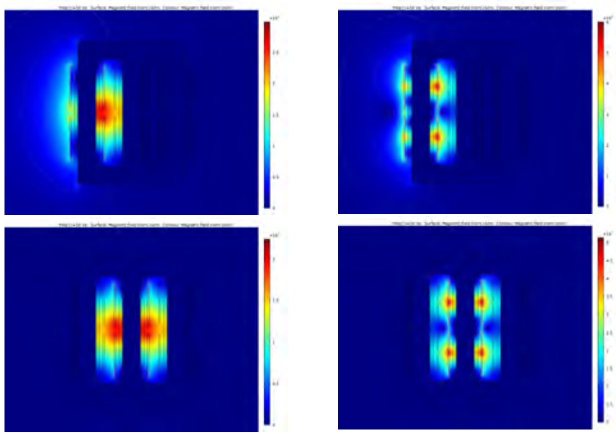
# GIMC TRANSFORMER DESIGN

## Degree of freedom

- HV windings interleaving
- Leakage inductance (i.e., branch inductance) tuning

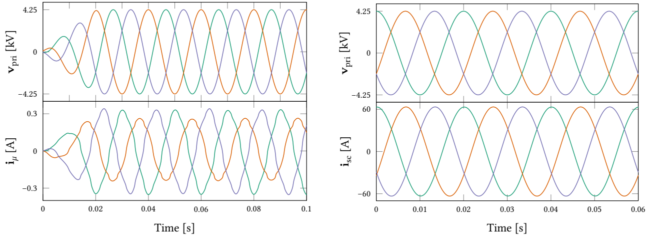



$L_{\sigma,\mathrm{HV}} = \{83.33, 108.21, 83.33\}$ [mH] $L_{\sigma,\mathrm{HV}} = \{25.57, 31.17, 25.57\}$ [mH]



▲ Leakage H-fields

▼ Time domain simulations (← no-load / → short-circuit)



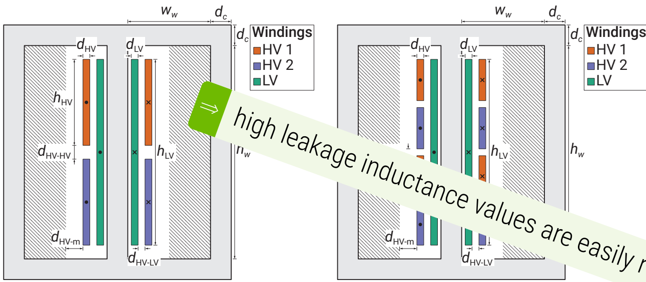

## Best design

- $w_w = 259.8$ mm and $\alpha = 4$
- $V_{tot} = 573.1$ l
- $P_{w,\mathrm{HV}} = 63.29$ W and $P_{w,\mathrm{LV}} = 30.93$ W

# GIMC TRANSFORMER DESIGN

**Degree of freedom**

- HV windings interleaving
- Leakage inductance (i.e., branch inductance) tuning

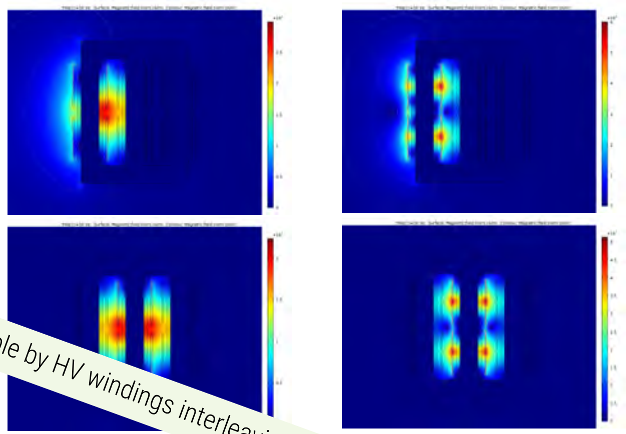



⇒ high leakage inductance values are easily reachable by HV windings interleaving (+ positioning)

**Best design**

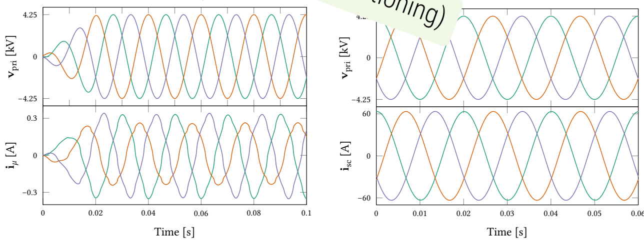
- $w_w = 259.8$ mm and $\alpha = 4$
- $V_{tot} = 573.1$ l
- $P_{w,HV} = 63.29$ W and $P_{w,LV} = 30.93$ W

$L_{\sigma,HV} = \{83.33, 108.21, 83.33\}$ [mH] $\quad L_{\sigma,HV} = \{25.57, 31.17, 25.57\}$ [mH]



▲ Leakage H-fields

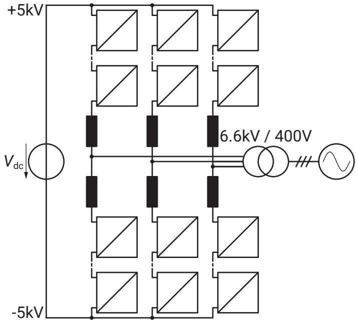
▼ Time domain simulations (← no-load /



# MAGNETIC COMPONENTS COMPARISON

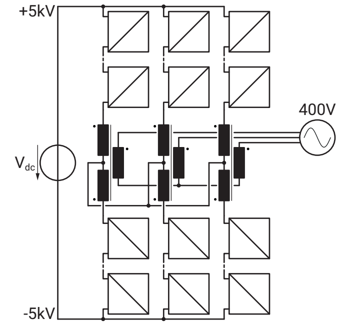
**Case 1** MMC

- 6 branch inductors + conventional LFT




**Case 2** GIMC

- no branch inductors + multi-windings transformer

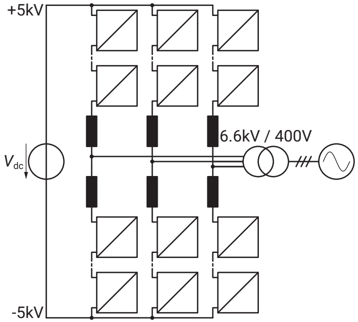



| | Branch inductors | | Transformer | |
|---|---|---|---|---|
| | volume | losses | volume | losses |
| DC/3-AC MMC | 6× 6 l | 780 W (0.156 %) | 481.7 l | 660 W (0.132 %) |
| GIMC | - | - | 573.1 l | 945 W (0.19 %) |

# MAGNETIC COMPONENTS COMPARISON

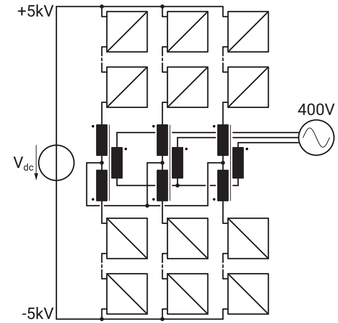
**Case 1** MMC

- 6 branch inductors + conventional LFT




**Case 2** GIMC

- no branch inductors + multi-windings transformer




| | Branch inductors | | Transformer | |
|---|---|---|---|---|
| | volume | losses | volume | losses |
| DC/3-AC MMC | 6× 6 l | 780 W (0.156 %) | 481.7 l | 660 W (0.132 %) |
| GIMC | - | - | 573.1 l | 945 W (0.19 %) |

⇒ volume + cost reduction & efficiency increase with the integrated magnetic component

# MV MMC CONVERTER PLATFORM

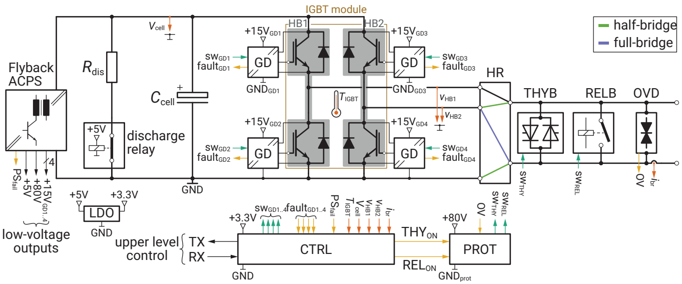
*University lab prototype*

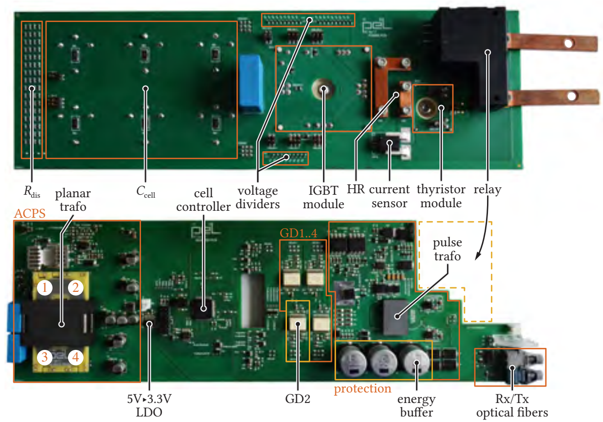
# MMC CELL @ PEL

## Ratings

- 0.5 MVA apparent power
- 10 kV MVdc connection
- 400 V / 6 kV ac output
- 96 cells (16 per branch)

## Cell concept




▲ Circuit partitioning

▼ Assembled cell

## Design

- 1.2 kV / 50 A IGBT module (Semikron SK50GH12T4T)
- 1.2 kV / 70 A Thyristor module (Semikron SK70KQ)
- $C_{sm}$ = 2.25 mF (6x Exxalia SnapSiC 4P 1500 µF, 400 V)
- Current sensor (Allegro ACS759 100 A)
- Bypass relay (KG K100 B-D012 X P)
- TI TMS320F28069 DSP
- Integrated Flyback auxiliary cell power supply from DC link with planar trafo

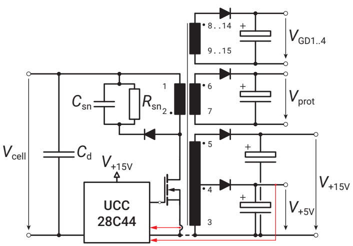
# AUXILIARY CELL POWER SUPPLY (I)

## Possible concepts

- Externally supplied
  - Single wire loop
  - Siebel
  - Inductive power transfer
- Internally supplied
  - Tapped inductor Buck
  - Flyback

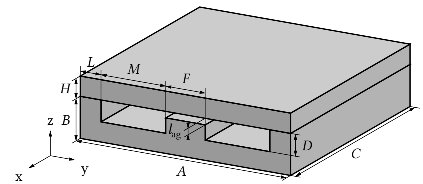
## Choice

- Flyback with 6 isolated secondaries
  - 1× 5 V, 4 W for the controller supply ($V_{+5V}$). This output is tightly regulated in closed-loop.
  - 4× 15 V, 1.5 W for the IGBT gate drivers ($V_{GD1..4}$)
  - 1× 80 V, 15 W for 15 s operation when activated for the protection circuit ($V_{prot}$)



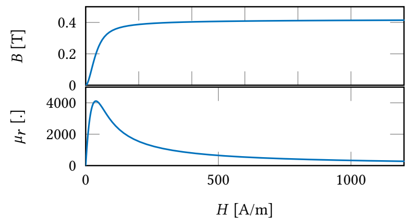

## Planar trafo design

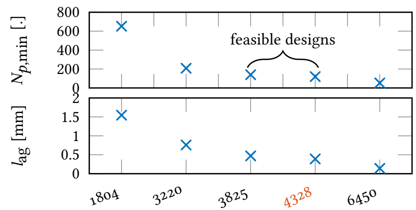
- PCB windings (isolation requirements!)
- Planar ferrite cores with custom gapping (COSMO ferrites)




## Matlab design tool

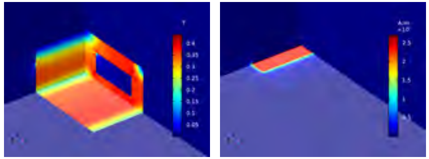
- Account for flux fringing [35]
- BH curve for CF297
- Jiles-Atherton parametrization

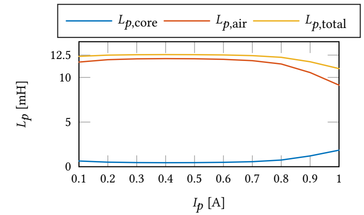



## FEM

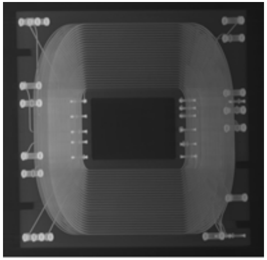
- Validate Matlab design
- 3D model for accurate leakage flux

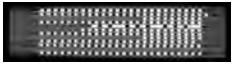




## Transformer assembly

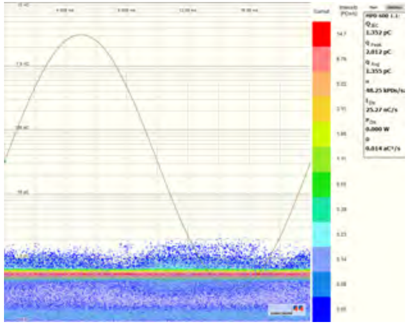
- 14 copper layers PCB
- Custom gapped ferrite E+I core



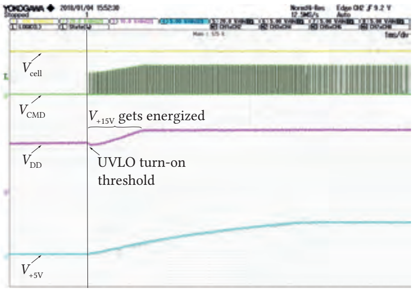


## AC dielectric withstand test

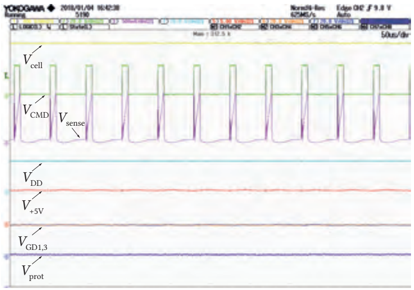
- Way below threshold level of 10pC



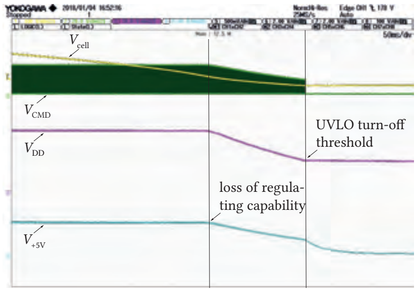
## Tests




▲ Start-up




▲ Steady-state operation




▲ Shut-down (slow $dv/dt$ from Delta power-supply used to emulate the cell)

# COFFEE BREAK

**Before the Coffee Break**

**1) Introduction and Motivation**
- Medium Voltage Direct Current Applications
- Modular Multilevel Converters
- Solid State Transformers

**2) Modular Multilevel Converter**
- Operating principles
- Pulse Width Modulation
- Control

**3) Galvanically Isolated Modular Converter**
- Magnetic Integration
- Design Optimization
- Sub-Module Design

**After the Coffee Break**

**4) High Power DC-DC Conversion**
- Dual Active Bridge Converters
- Resonant Converters
- Medium Frequency Conversion

**5) Medium Voltage DC-DC Conversion**
- MMC-based Conversion
- Quasi-Two-Level Converters
- Design and Control

**6) MMC-Based DC-DC Converters**
- Scott Transformer Connection
- Bidirectional vs. Unidirectional
- Design and Control

# DC-DC CONVERTERS

*Building blocks of Solid State Transformers*

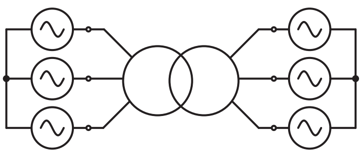
# SOLID-STATE TRANSFORMER (SST)

### Concept and motivation?

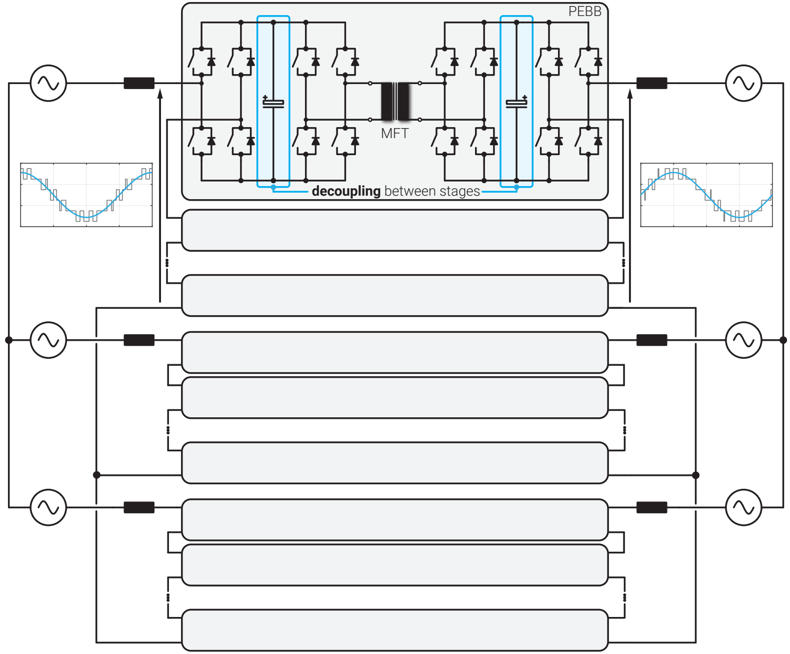
- SST = Switching stages + Isolation
- Firstly envisioned within AC grids
- Power Electronic Building Blocks (PEBBs)
- Conventional transformer vs SST?
- Operating frequency increase **(MFT)**

| | Grid Tx | SST |
|---|---|---|
| Controlability | No | Yes |
| Efficiency | $\eta \geq 99\%$ | $P_\gamma$ |
| Q compensation | No | Yes |
| Fault tolerance | No | Yes |
| Size | Bulky | Compact |

**Advantages at the expense of reduced efficiency!**



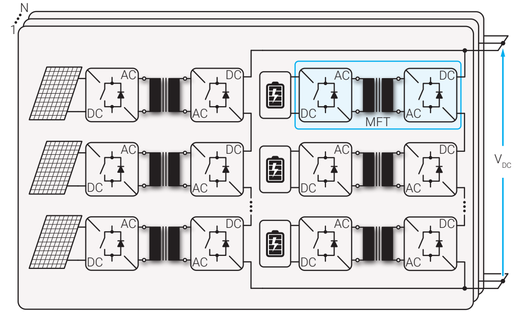
▲ Conventional AC grid transformer



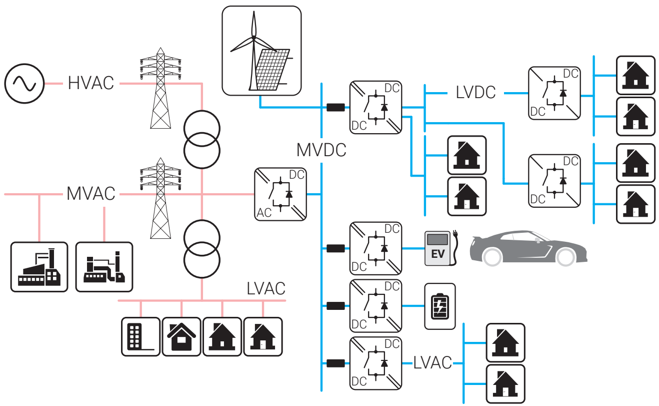

▲ Solid-State Transformer employed with the aim of interfacing two AC systems [36], [37]

# DC-DC SST

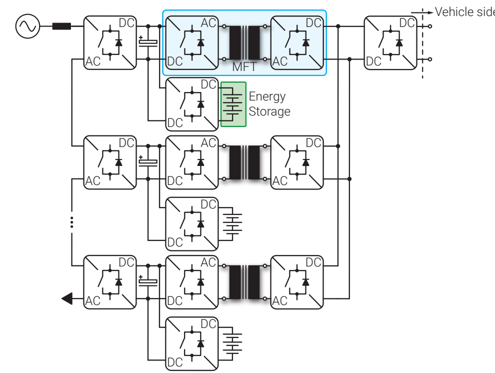
- Inherent part of the AC-AC SST
- Expansion of the existing power system
- Enabling technology for MVDC
- Penetration of renewable energy sources
- Fast / Ultra Fast EV charging
- **Medium Frequency** conversion




▲ Employment of a DC-DC SST within RES-based systems



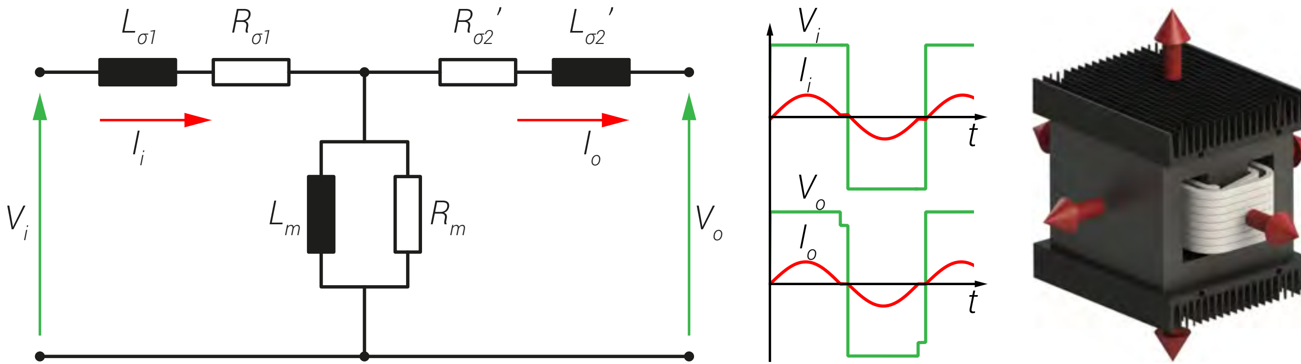

▲ Concept of a modern power system




▲ Fast EV charging concept

# MFT CHALLENGES

- **Skin and proximity effect losses:** impact on efficiency and heating
- **Cooling:** increase of power density $\Rightarrow$ decrease in size $\Rightarrow$ less cooling surface $\Rightarrow$ higher $R_{th}$ $\Rightarrow$ higher temperature gradients
- **Non-sinusoidal excitation:** impact on core and winding losses and insulation
- **Insulation:** coordination and testing taking into account high $\frac{dV}{dt}$ characteristic for power electronic converters
- **Accurate electric parameter control:** especially in case of resonant converter applications

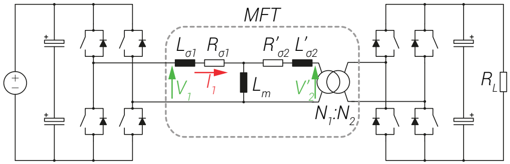


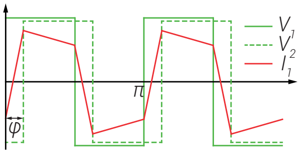

▲ Medium Frequency Transformer challenges

$\Rightarrow$ MFT design is generally challenging and requires multiphysics considerations and multiobjective optimization

# MFT NONSINUSOIDAL POWER ELECTRONIC WAVEFORMS

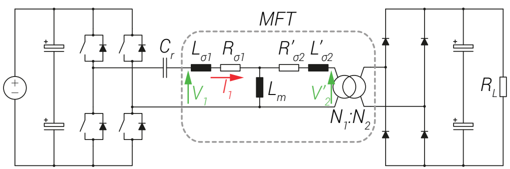
**DAB Converter:**

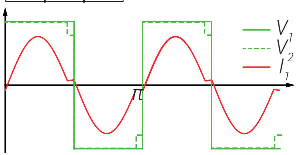



- $V_{1,2}$ square
- $I$ non-sinusoidal

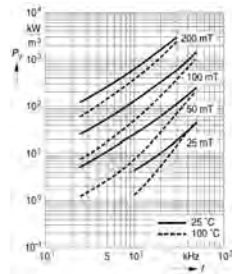
**Series Resonant Converter:**




- $V_{1,2}$ square
- $I$ sinusoidal

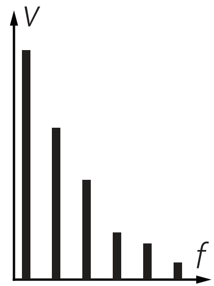
**Core Losses:**




▲ Specific AC core losses

- Data-sheet - sinusoidal excitation
- Steinmetz - sinusoidal excitation losses
- Core is excited with square pulses!
- Losses must be correctly evaluated
- Generalization of Steinmetz model

**Winding Losses:**

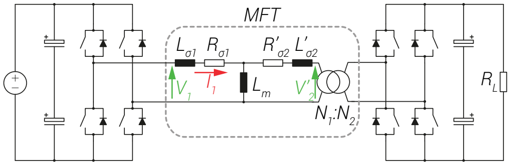


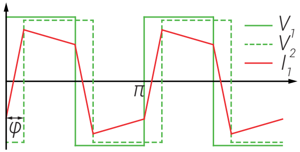

▲ Harmonics impacting winding losses

- Current waveform impacts the winding losses
- Copper is a linear material
- Losses can be evaluated in harmonic basis
- Current harmonic content must be evaluated
- Losses are the sum of the individual harmonic losses

# MFT ACCURATE PARAMETERS CONTROL

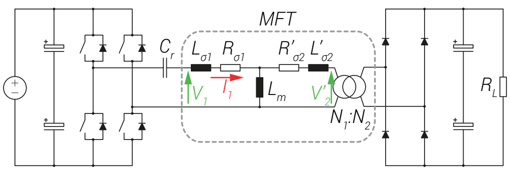
**DAB Converter:**

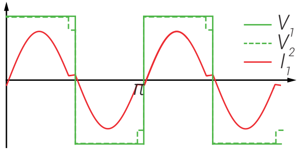



- $V_{1,2}$ square
- $I$ non-sinusoidal

**Series Resonant Converter:**




- $V_{1,2}$ square
- $I$ sinusoidal

**DAB**

- Leakage Inductance
- Controllability of the power flow
- Higher than $L_{\sigma.min}$ :

$$L_{\sigma.min} = \frac{V_{DC1}V_{DC2}\varphi_{min}(\pi - \varphi_{min})}{2P_{out}\pi^2 f_s n}$$

- Magnetizing Inductance is normally high

**SRC**

- Leakage inductance is part of resonant circuit
- Must match the reference:

$$L_{\sigma.ref} = \frac{1}{\omega_0^2 C_r}$$

- Magnetizing inductance is normally high
- Reduced in case of LLC
- Limits the magnetization current to the reference $I_{m.ref}$
- Limits the switch-off current and losses

$$L_m = \frac{nV_{DC2}}{4f_s I_{m.ref}}$$

- $I_{m.ref}$ has to be sufficiently high to maintain ZVS

# MFT VARIETY OF DESIGNS...

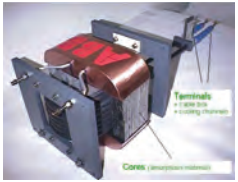
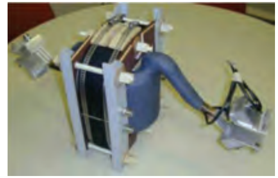
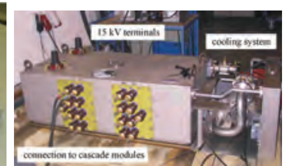



ABB: 350kW, 10kHz

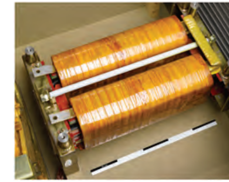
ABB: 3x150kW, 1.8kHz



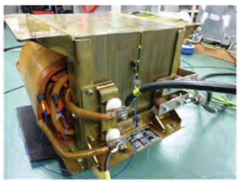
BOMBARDIER: 350kW, 8kHz




ALSTOM: 1500kW, 5kHz

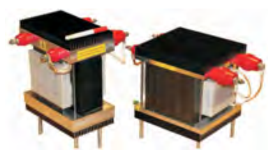


IKERLAN: 400kW, 5kHz

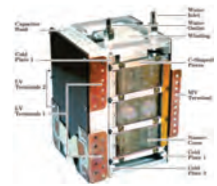


IKERLAN: 400kW, 1kHz

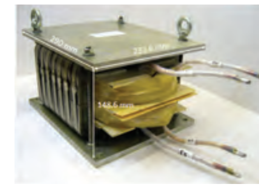
FAU-EN: 450kW, 5.6kHz



CHALMERS: 50kW, 5kHz

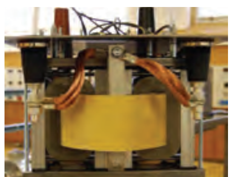


ETHZ: 166kW, 20kHz

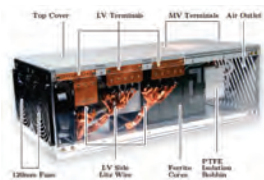


EPFL: 300kW, 2kHz

STS: 450kW, 8kHz



KTH: 170kW, 4kHz




ETHZ: 166kW, 20kHz

EPFL: 100kW, 10kHz

?

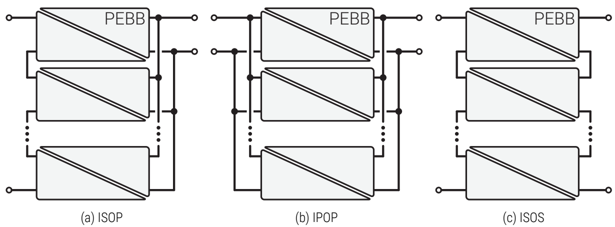
ACME: ???kW, ???kHz

# HP DC-DC CONVERTERS

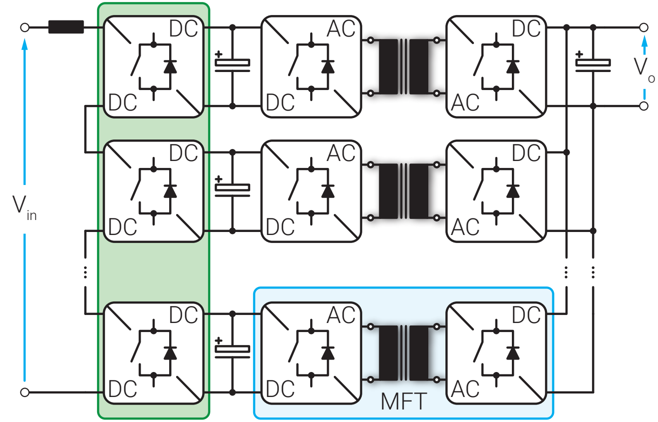
*Going into Medium Voltage..*

## Fractional power processing

- Multiple MFTs
- Equal power distribution among PEBBs
- MFT isolation?
- Various PEBB configurations



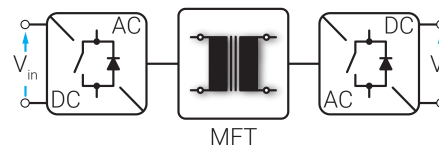

▲ Different structures employed depending upon the voltage level




▲ ISOP Structure

## Bulk power processing

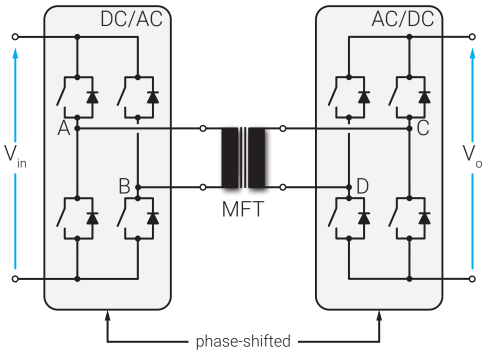
- Single MFT
- Isolation solved only once
- Various configurations/operating principles

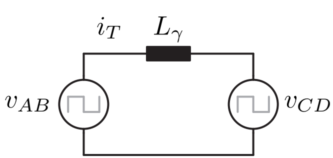



▲ Bulk power processing concept

# COMMON PEBB CONFIGURATIONS

## Dual-Active Bridge

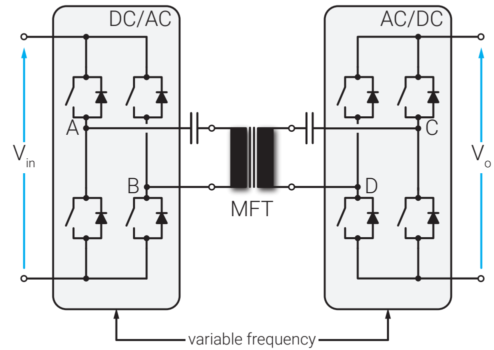


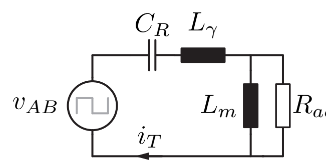




$$P = P(\varphi)$$

▲ Dual Active Bridge [38]

## Resonant Converters




$$f_{r1} = \frac{1}{2\pi\sqrt{C_R L_\gamma}}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{C_R (L_\gamma + L_m)}}$$

$$Q = Q(R_{ac})$$

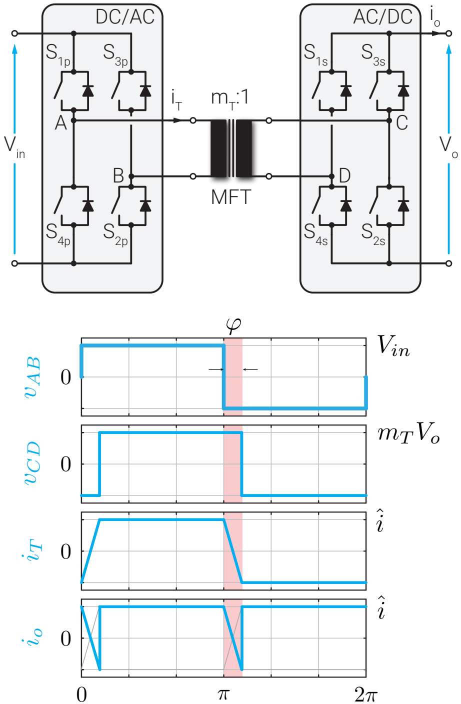
$$G = G\left(\frac{f_{sw}}{f_{r1}}, \frac{L_m}{L_\gamma}, Q\right)$$

▲ LCL Resonant Converter

# 1-PHASE DAB

*Basic operating principles*

# SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



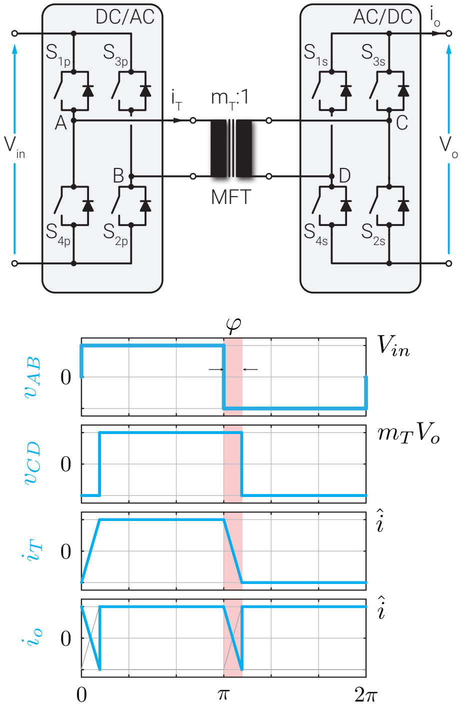

▲ 1PH-DAB with its relevant waveforms

**Power equation**

$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma}\varphi\left(1 - \frac{|\varphi|}{\pi}\right)$$

# SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)

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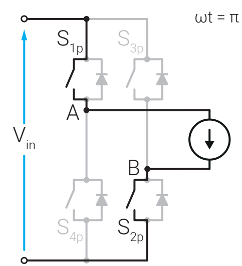
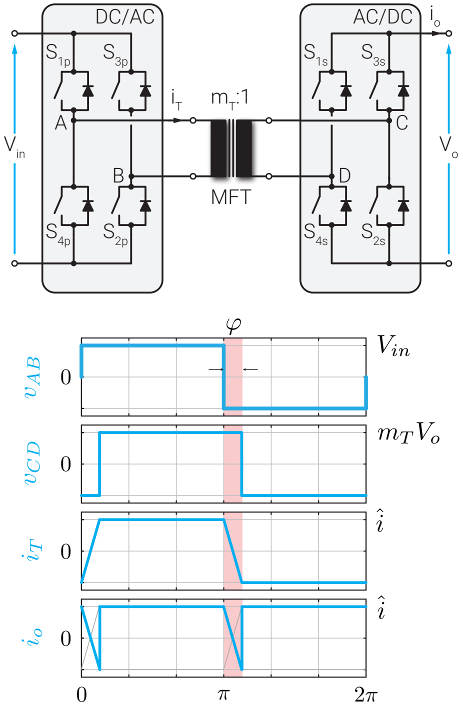
$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(1 - \frac{|\varphi|}{\pi}\right)$$

## Switching cycle



# SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)

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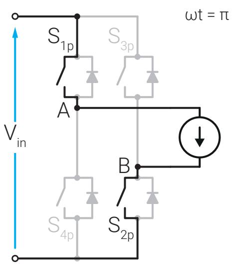
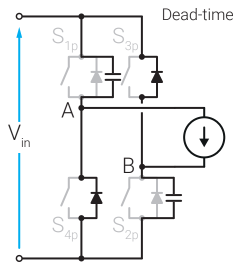
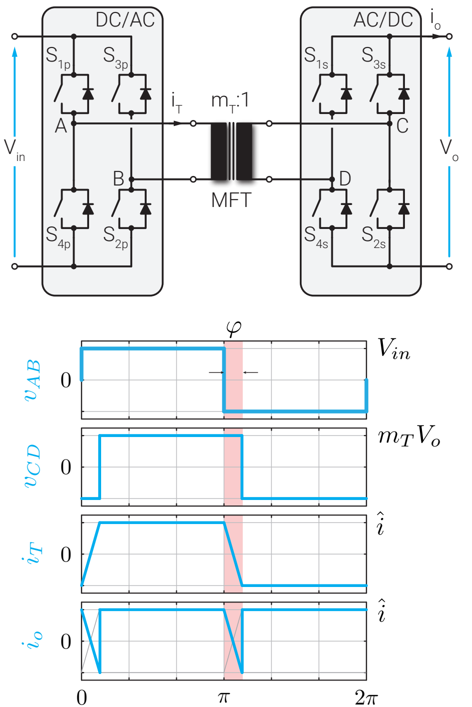
## Switching cycle



# SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



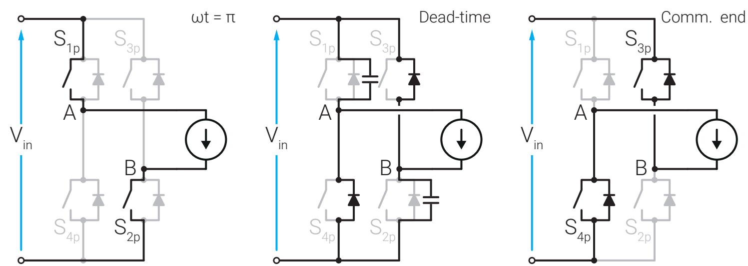

▲ 1PH-DAB with its relevant waveforms

## Power equation

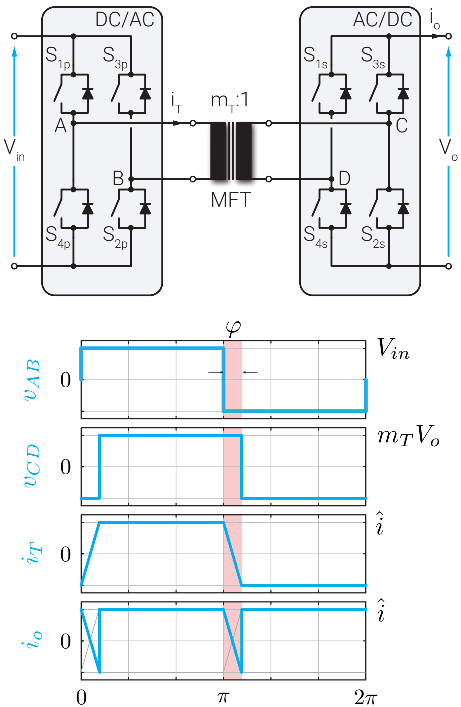
$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(1 - \frac{|\varphi|}{\pi}\right)$$

## Switching cycle



# SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)




▲ 1PH-DAB with its relevant waveforms

## Power equation

$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

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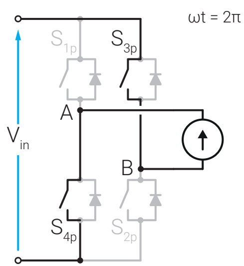
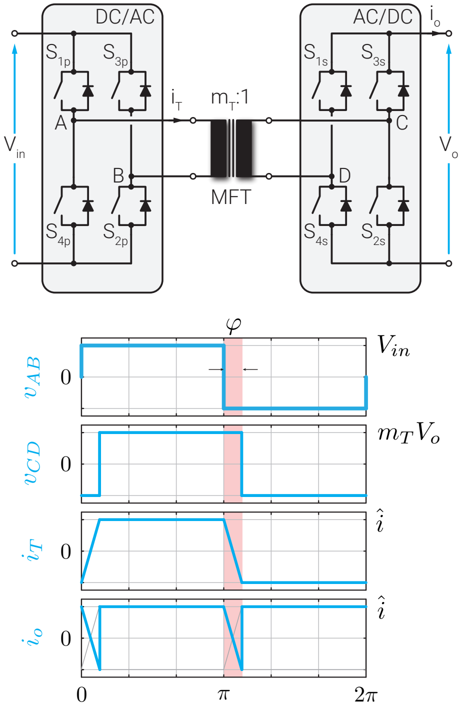
## Switching cycle



# SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)




▲ 1PH-DAB with its relevant waveforms

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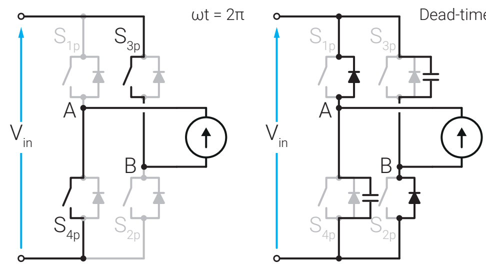
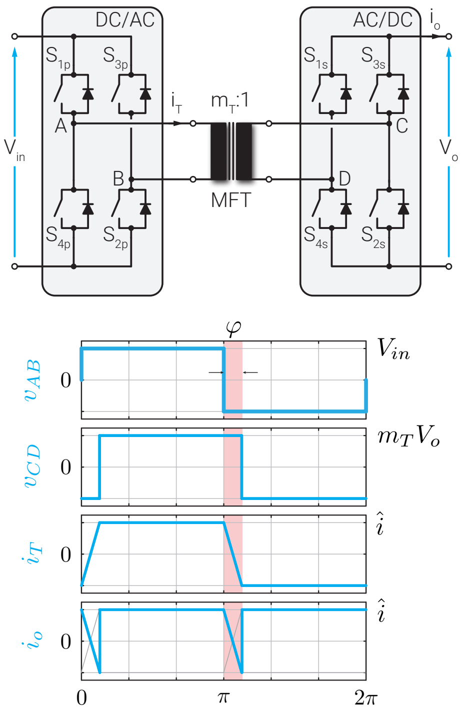
$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(1 - \frac{|\varphi|}{\pi}\right)$$

## Switching cycle



# SINGLE-PHASE (1PH) DUAL ACTIVE BRIDGE (DAB)



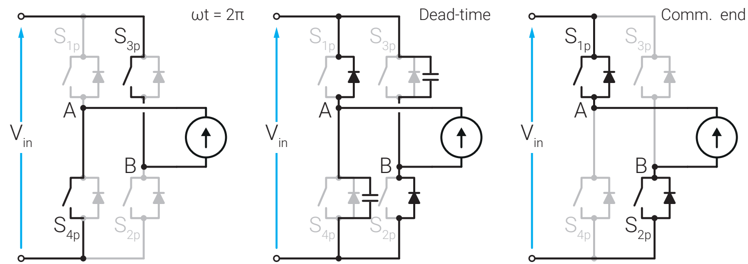

▲ 1PH-DAB with its relevant waveforms

## Power equation

$$P = \frac{1}{T}\int_0^T v_{AB} i_T dt$$

$$= m_T \frac{V_{in} V_o}{\omega L_\Sigma} \varphi \left(1 - \frac{|\varphi|}{\pi}\right)$$

## Switching cycle



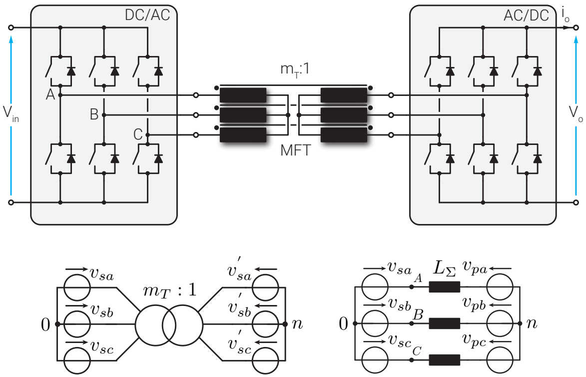

## Main featuress

- Phase-Modulated converter
- Simple power flow control
- Soft-switching capability

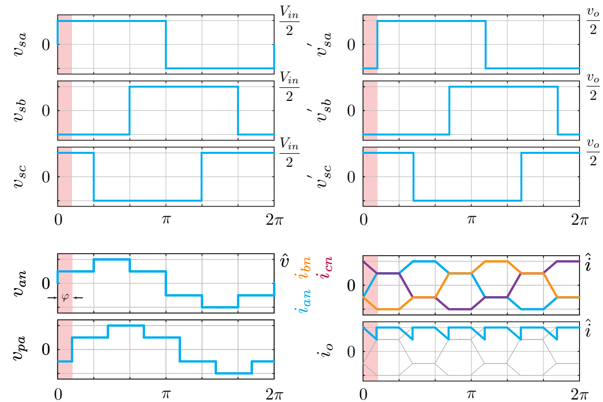
# 3-PHASE DAB

*Somewhat more complicated...*

# THREE-PHASE (3PH) DAB




$$v_{an} = \frac{2v_{sa} - v_{sb} - v_{sc}}{3} \qquad v_{pa} = m_T \frac{2v'_{sa} - v'_{sb} - v'_{sc}}{3}$$




▲ 3PH-DAB with its relevant waveforms

## Power Equation

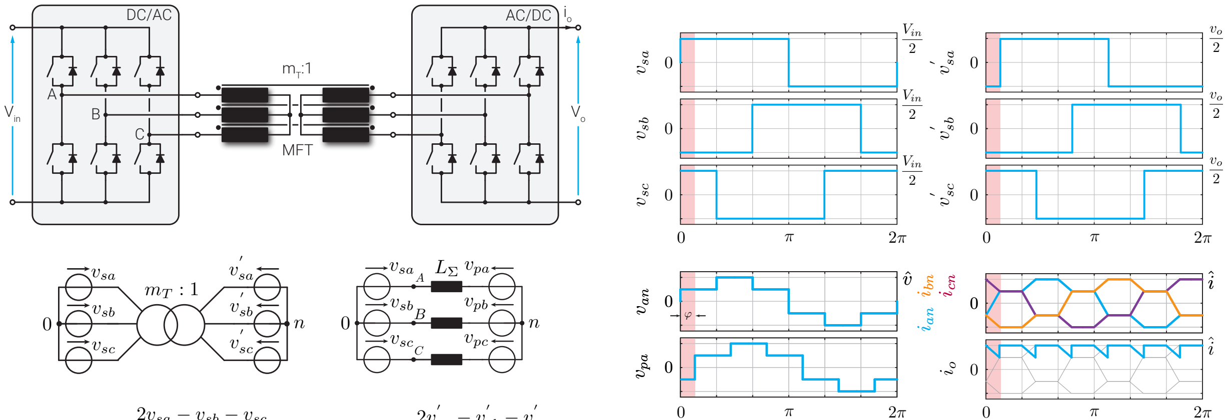
$$P = \frac{3}{T}\int_0^T v_{an} i_{an}\, dt$$

$$= m_T \frac{4}{3}\frac{V_{in}V_o}{\omega L_\Sigma}\varphi\left(\frac{1}{2} - \frac{3|\varphi|}{8\pi}\right)$$

## 1-PH vs 3-PH DAB

| | Control Simplicity | Tx utilization | Soft Switching | In/Out current ripple |
|---|---|---|---|---|
| **1-PH DAB** | ☺ | ☹ | ☺ | ☹ |
| **3-PH DAB** | ☺ | ☺ | ☺ | ☺ |

# THREE-PHASE (3PH) DAB




$$v_{an} = \frac{2v_{sa} - v_{sb} - v_{sc}}{3} \qquad v_{pa} = m_T \frac{2v'_{sa} - v'_{sb} - v'_{sc}}{3}$$

▲ 3PH-DAB with its relevant waveforms

## Power Equation

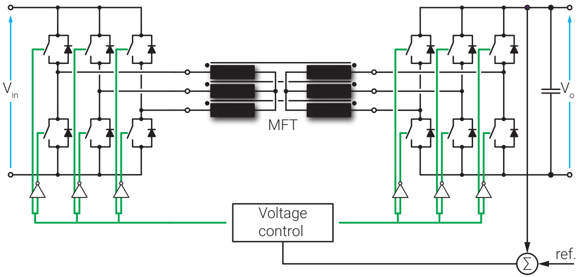
$$P = \frac{3}{T}\int_0^T v_{an} i_{an} dt$$

$$= m_T \frac{4}{3}\frac{V_{in}V_o}{\omega L_\Sigma}\varphi\left(\frac{1}{2} - \frac{3|\varphi|}{8\pi}\right)$$

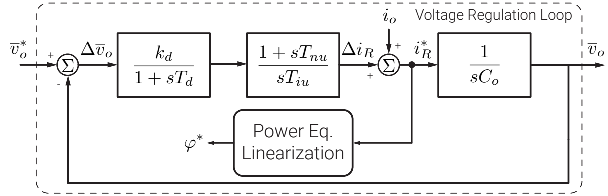
## 1-PH vs 3-PH DAB

| | Control Simplicity | Tx utilization | Soft Switching | In/Out current ripple |
|---|---|---|---|---|
| **1-PH DAB** | ☺ | ☹ | ☺ | ☹ |
| **3-PH DAB** | ☺ | ☺ | ☺ | ☺ |

⇒ 3PH-DAB is considered favorable!




▲ Observed DAB-based system



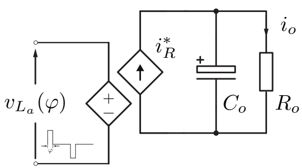

▲ Output voltage control loop

Assuming $P_{in} = P_{out}$:

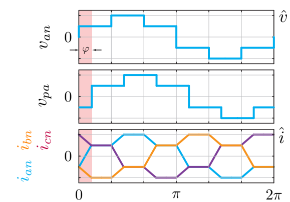
$$\cancel{V_o} i_o = \frac{4 m_T V_{in} \cancel{V_o}}{3\omega L}\varphi\left(\frac{1}{2} - \frac{3|\varphi|}{8\pi}\right)$$

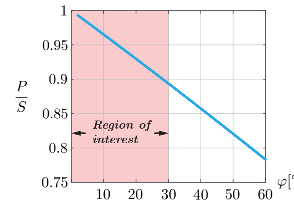
$$\Rightarrow i_o = \frac{4 m_T V_{in}}{3\omega L}\varphi\left(\frac{1}{2} - \frac{3|\varphi|}{8\pi}\right)$$

⇒ Controlled current source behavior!

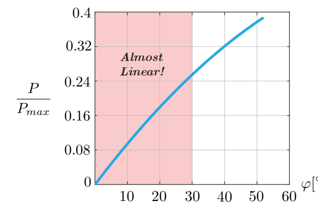


▲ DAB equivalent circuit seen from the controlled side



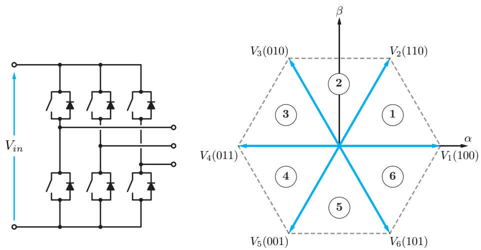



$$\boxed{\frac{P}{S} = \frac{4\pi - 3\varphi}{2\pi\sqrt{\frac{4\pi - \varphi}{\pi}}}}$$

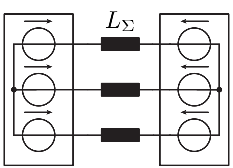


# ABRUPT PHASE ANGLE CHANGES? (I)

- Six step modulation
- Limited number of voltage states




▲ Either side of the 3PH-DAB




$$\mathbf{v_p} = \hat{V}\angle\varphi \qquad \mathbf{v_s} = \hat{V}\angle 0$$

▲ DAB equivalent circuit

? Current shape in the $\alpha\beta$ plane?

For $\omega t \in [(k-1)\frac{\pi}{3}, k\frac{\pi}{3}]$

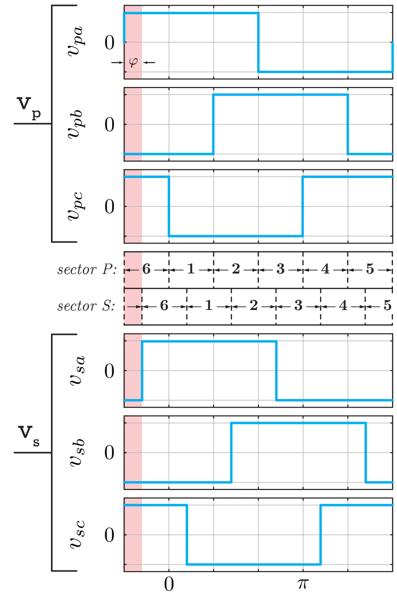
$$\mathbf{V_p} = \mathbf{V_k}$$

$$\mathbf{V_s} = \begin{cases} \mathbf{V_{k-1}}, & \omega t \in [(k-1)\frac{\pi}{3}, (k-1)\frac{\pi}{3}+\varphi] \\ \mathbf{V_k}, & \omega t \in [(k-1)\frac{\pi}{3}+\varphi, k\frac{\pi}{3}] \end{cases}$$

$$L\frac{d\mathbf{i}}{dt} = \mathbf{V_p} - \mathbf{V_s}$$

$$= \begin{cases} \hat{V}e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}, (k-1)\frac{\pi}{3}+\varphi] \\ 0, & \omega t \in [(k-1)\frac{\pi}{3}+\varphi, k\frac{\pi}{3}] \end{cases}$$

$$\mathbf{i} = \begin{cases} \mathbf{i_{0,k}} + \frac{\hat{V}}{L_\Sigma} t e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}, (k-1)\frac{\pi}{3}+\varphi] \\ \mathbf{i_{0,k}} + \frac{\hat{V}}{\omega L_\Sigma}\varphi\, e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}+\varphi, k\frac{\pi}{3}] \end{cases}$$




▲ DAB switching signals

# ABRUPT PHASE ANGLE CHANGES? (I)

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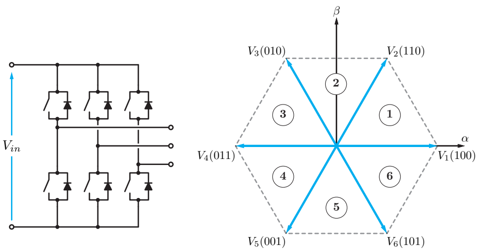
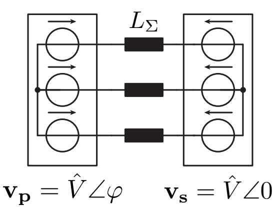
- Limited number of voltage states




▲ Either side of the 3PH-DAB

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$$L\frac{d\mathbf{i}}{dt} = \mathbf{V_p} - \mathbf{V_s}$$

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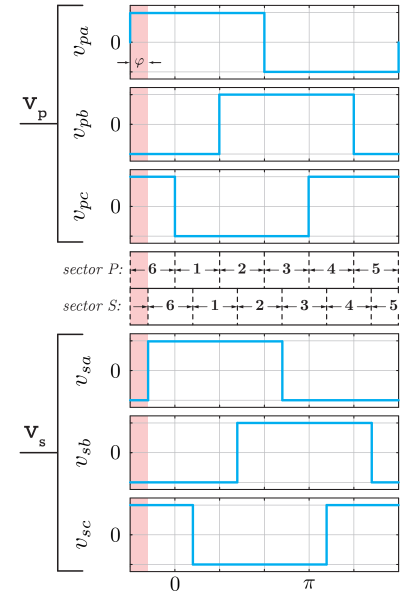
$$\mathbf{i} = \begin{cases} \mathbf{i_{0,k}} + \frac{\hat{V}}{L_\Sigma} t e^{j(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}, (k-1)\frac{\pi}{3}+\varphi] \\ \mathbf{i_{0,k}} + \frac{\hat{V}}{\omega L_\Sigma}\varphi\, e^{j\,(k+1)\frac{\pi}{3}}, & \omega t \in [(k-1)\frac{\pi}{3}+\varphi, k\frac{\pi}{3}] \end{cases}$$

- Amplitude of the change proportional to $\varphi$
- Phase change in $60^\circ$ steps

⇒ Current slides along a hexagon!




▲ DAB switching signals

# ABRUPT PHASE ANGLE CHANGES? (II)

**Recap**

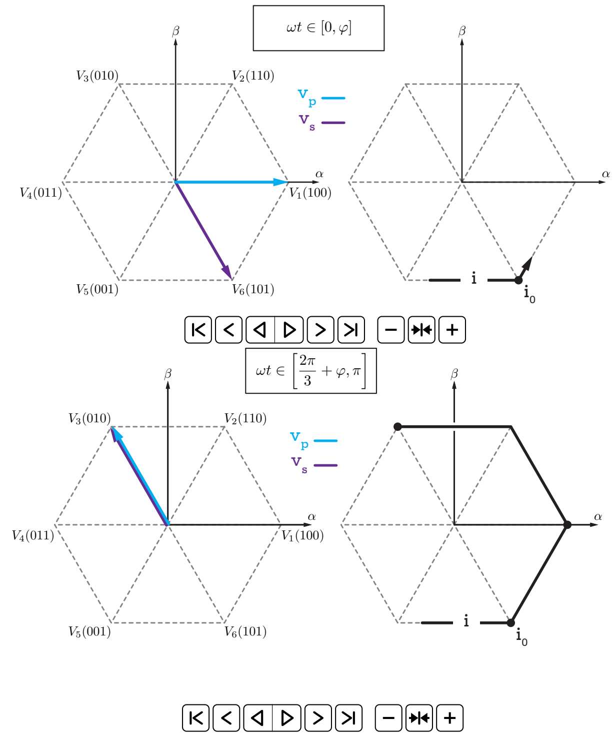
- Limited number of voltage states $V_p$ and $V_s$
- Current vector stepwise phase changes ($60^{\circ}$)
- Current vector magnitude directly proportional to phase angle
- Current vector slides along the hexagon [39], [40]

# ABRUPT PHASE ANGLE CHANGES? (II)

**Recap**

- Limited number of voltage states $V_p$ and $V_s$
- Current vector stepwise phase changes ($60^\circ$)
- Current vector magnitude directly proportional to phase angle
- Current vector slides along the hexagon [39], [40]

> ? What if the phase angle gets abruptly changed?



# ABRUPT PHASE ANGLE CHANGES? (II)

## Recap

- Limited number of voltage states $V_p$ and $V_s$
- Current vector stepwise phase changes ($60^\circ$)
- Current vector magnitude directly proportional to phase angle
- Current vector slides along the hexagon [39], [40]

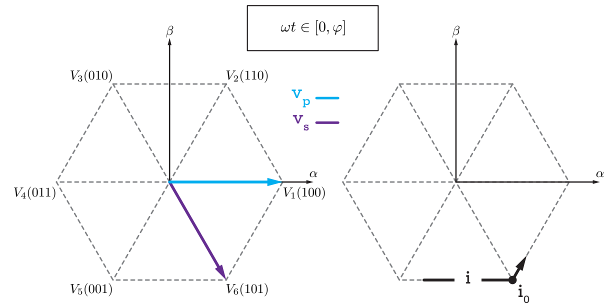
> ? What if the phase angle gets abruptly changed?

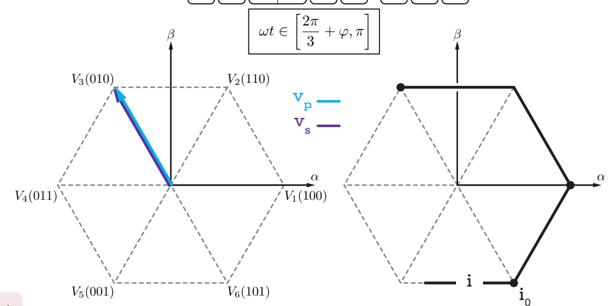
- New current vector trajectory
- Hexagon decentralization $\Rightarrow$ Transformer currents asymmetry!

**Inverse $\alpha\beta0$ transformation:**

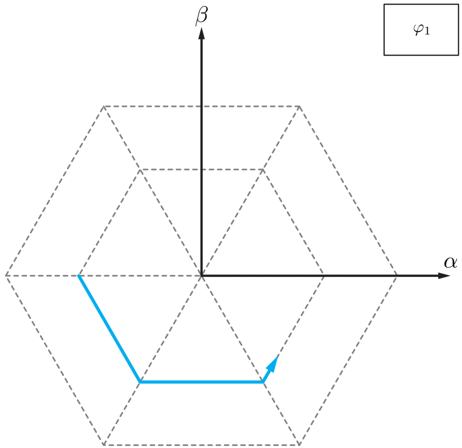
$$\begin{bmatrix} i_a^{off} \\ i_b^{off} \\ i_b^{off} \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \cdot \begin{bmatrix} i_{\alpha,hex}^{off} \\ i_{\beta,hex}^{off} \\ 0 \end{bmatrix}$$

> ϟ Time constant $L_\Sigma/R_\Sigma$ determines asymmetric components decay!

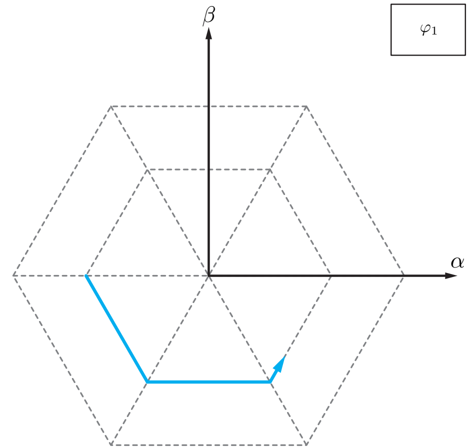


# ABRUPT PHASE ANGLE CHANGES? (III)




▲ Safe way of achieving phase angle change (I)




▲ Safe way of achieving phase angle change (II)

## Applied phase angle sequence:

$$\underbrace{\underbrace{\varphi_1}_{\text{Angle change!}} \Rightarrow \underbrace{\frac{\varphi_1+\varphi_2}{2}}_{\frac{T}{6}} \Rightarrow \underbrace{\frac{\varphi_1+\varphi_2}{2}}_{\frac{T}{6}} \Rightarrow \underbrace{\frac{\varphi_1+\varphi_2}{2}}_{\frac{T}{6}}}_{\text{Transition time} = \frac{T}{2}} \Rightarrow \underbrace{\varphi_2}_{\text{Transition end}}$$

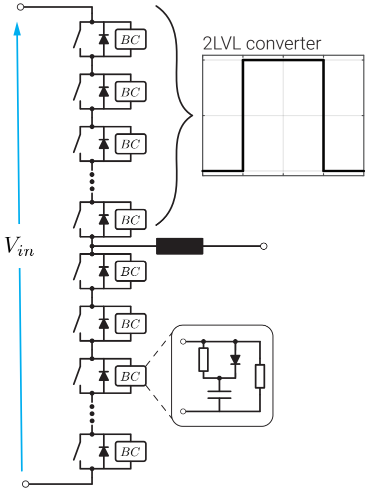
## Applied phase angle sequence:

$$\underbrace{\varphi_1}_{\text{Angle change!}} \Rightarrow \underbrace{\underbrace{\varphi_2}_{\frac{T}{6}} \Rightarrow \underbrace{\varphi_1}_{\frac{T}{6}}}_{\text{Transition time} = \frac{T}{3}} \Rightarrow \underbrace{\varphi_2}_{\text{Transition end}}$$

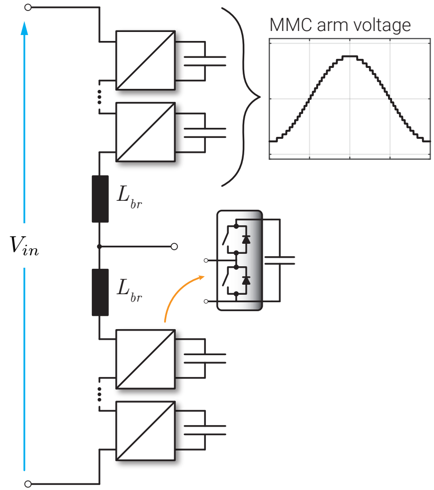
# MEDIUM VOLTAGE DC-DC

*Extending previously presented concepts...*

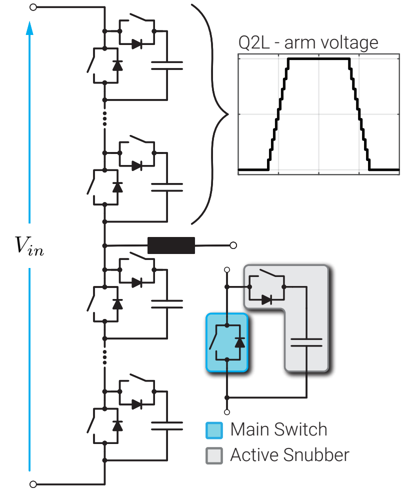
# HOW TO HANDLE HIGH/MEDIUM VOLTAGES?




▲ Series connection of switches [41]




▲ Modular Multilevel Converter (MMC)




▲ Quasi Two-Level (Q2L) Converter [42], [43]

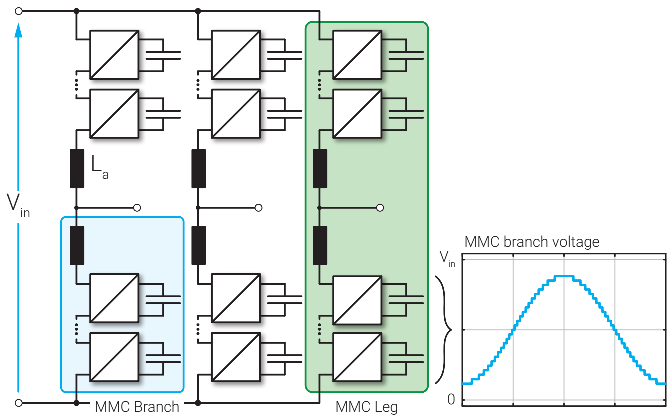
- Series connection of switches with snubbers
- Two voltage levels ($n_{LVL} = 2$)
- Two-Level voltage waveforms

- Series connection of Submodules (SM)
- $n_{LVL}$ depending upon number of SMs
- Arbitrary voltage waveform generation

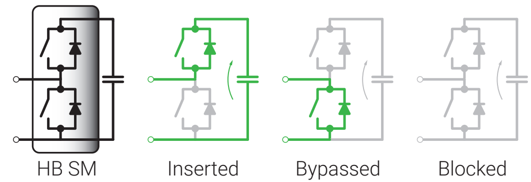
- Series connection of MMC-alike SMs
- $n_{LVL}$ depending upon number of SMs
- Quasi Two-Level (trapezoidal) voltage waveform

# MODULAR MULTILEVEL CONVERTER (MMC)

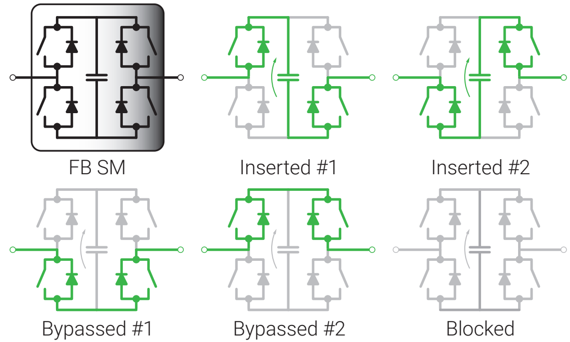
- Variety of conversion possibilities
- Variety of modulations
- Different types of submodules (SMs)
  - Half-Bridge (HB)
  - Full-Bridge (FB)
  - Others...
- Arbitrary voltage waveform generation




▲ Modular Multilevel Converter (MMC)



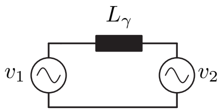

▲ Half-Bridge submodule and its allowed states



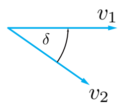

▲ Full-Bridge submodule and its allowed states

# MMC-BASED DUAL ACTIVE BRIDGE (DAB)

- Basic operation principles are retained
- Easy to comprehend (AC equivalent)

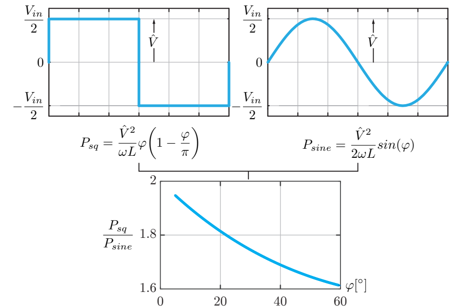


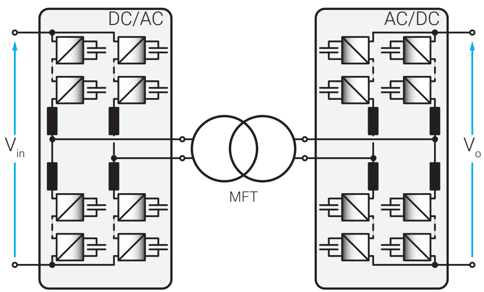

$$P = \frac{V_1 V_2}{\omega L_\gamma} sin(\delta)$$



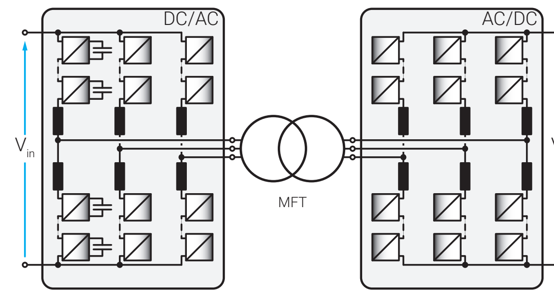

**Challenges?**

- Modulation choice (sine, square, etc ... ?)
- System design ($N$ vs $V_{grid}$)
- Energy balancing
- Q2L mode & capacitors sizing
- Engagement within bipolar grids




▲ MMC-based 1PH-DAB [44]




▲ MMC-based 3PH-DAB

# MMC-BASED DUAL ACTIVE BRIDGE (DAB)

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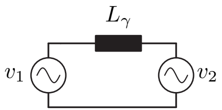
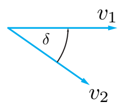
- Easy to comprehend (AC equivalent)




$$P = \frac{V_1 V_2}{\omega L_\gamma} sin(\delta)$$

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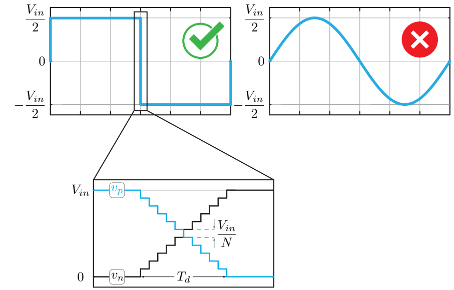
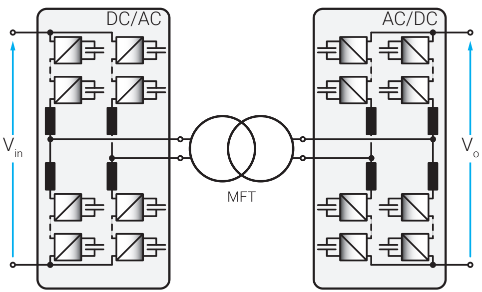
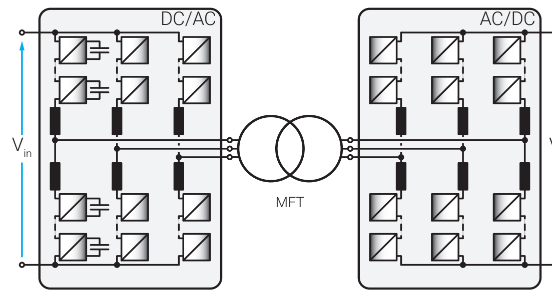


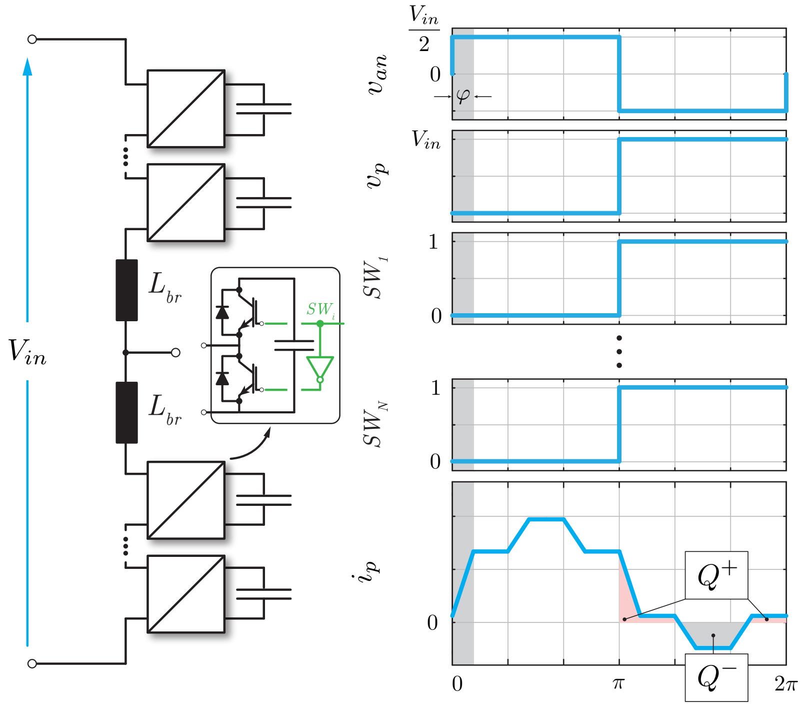




▲ MMC-based 1PH-DAB [44]




▲ MMC-based 3PH-DAB

# MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (I)

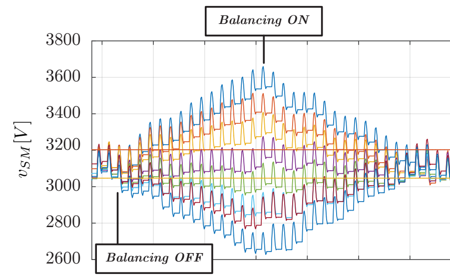


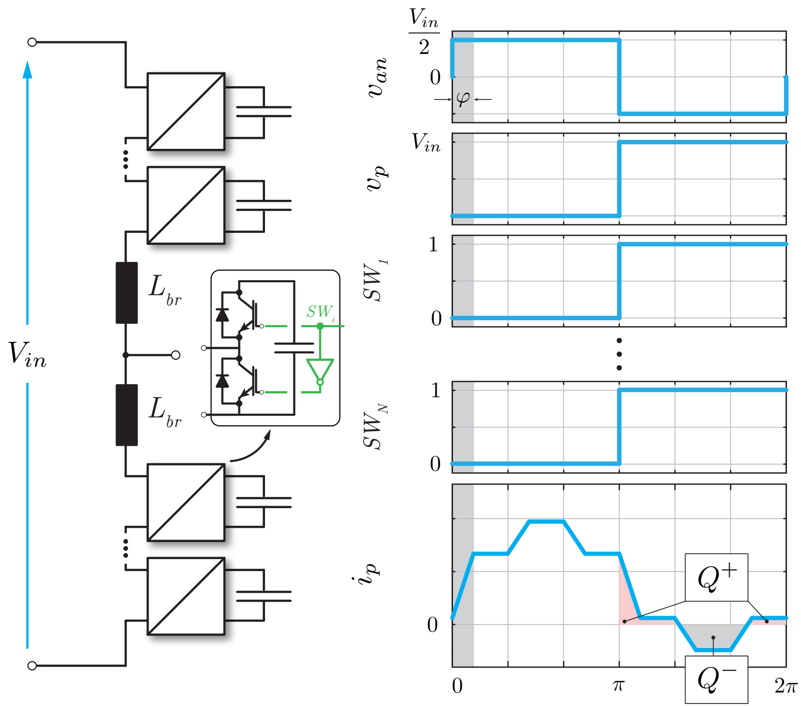

▲ MMC operating as a two level converter and its relevant waveforms

Ideally, $\boxed{Q^+ = Q^-}$ ⇒ **Natural balancing**

However, reality is different...

- Branch resistances affect the MMC current
- Not all the switches are gated at the same time



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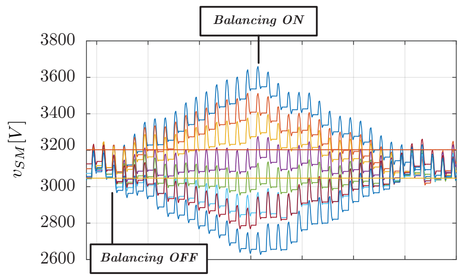
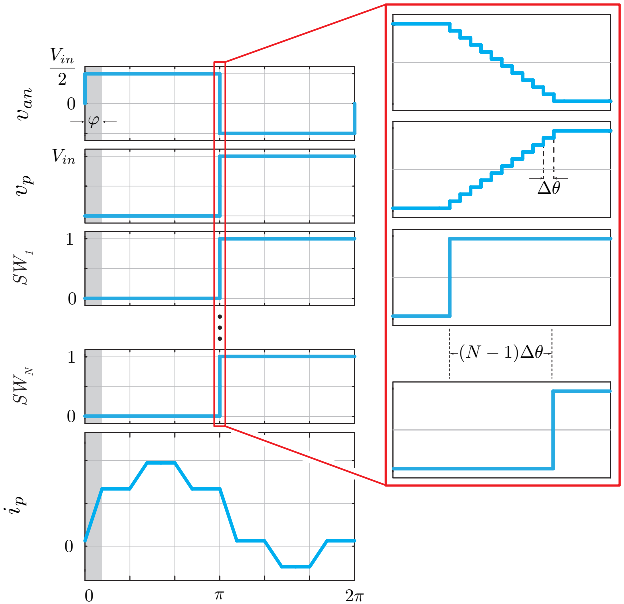



Balancing algorithm must be employed!

# MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (II)



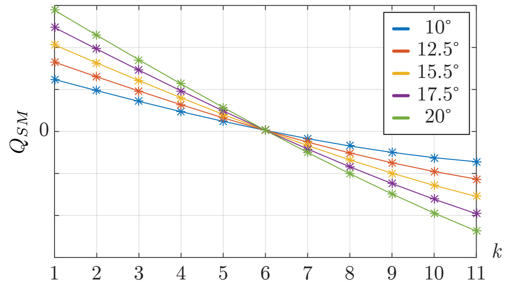

▲ MMC operating with quasi square voltages and its relevant waveforms

## Quasi Square Wave operation

- Intentional displacement among gating signals
- Control of MFT voltage slopes ($dV/dt$)
- Control of SMs' voltages!

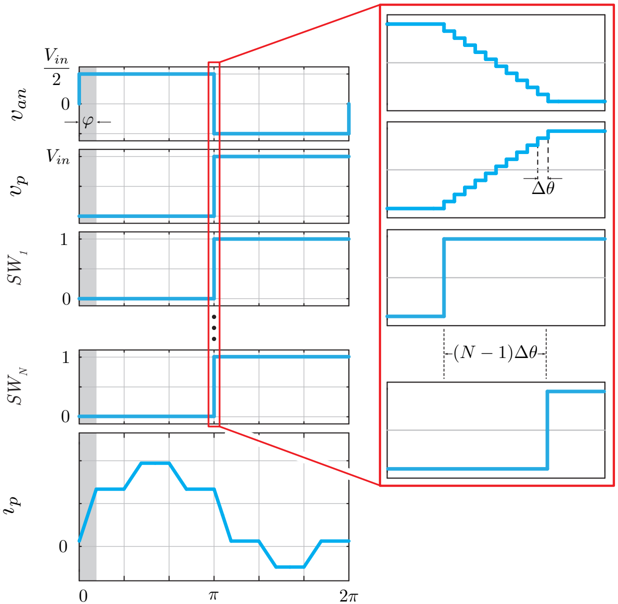
$$G = \frac{V_o m_T}{V_{in}}$$

For G = 1, SMs charge distribution can be derived.




▲ Charge received by a SM depending upon the gate signal [45]

# MMC ENERGY BALANCING AND QUASI SQUARE WAVE OPERATION (II)



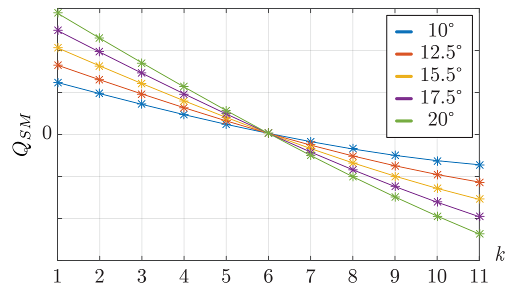

▲ MMC operating with quasi square voltages and its relevant waveforms

## Quasi Square Wave operation

- Intentional displacement among gating signals
- Control of MFT voltage slopes ($dV/dt$)
- Control of SMs' voltages!

$$G = \frac{V_o m_T}{V_{in}}$$

For G = 1, SMs charge distribution can be derived.




▲ Charge received by a SM depending upon the gate signal [45]

⇒ Different charge distribution enables balancing!

# MMC-BASED DAB SORTING FOR N = 3 (EXAMPLE)

- $V_{SM}(k)$ - SMs voltages measured in the observed switching period
- $V_{SM}(k-1)$ - SMs voltages measured in the previous switching period
- $Gate(k-1)$ - Gate signals assigned in the previous switching period
- $\Delta V_{SM}$ - SM voltage change with respect to the previous switching period

| | $SM_1$ | $SM_2$ | $SM_3$ |
|---|---|---|---|
| $V_{SM}$ (k) | 1200 | 1050 | 1150 |
| $V_{SM}$ (k-1) | 1100 | 1150 | 1200 |
| Gate (k-1) | Signal 2 | Signal 3 | Signal 1 |
| $\Delta V_{SM}$ | 100 | -100 | -50 |

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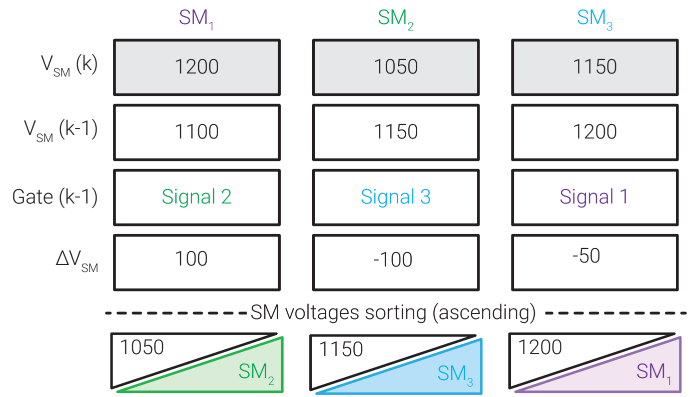

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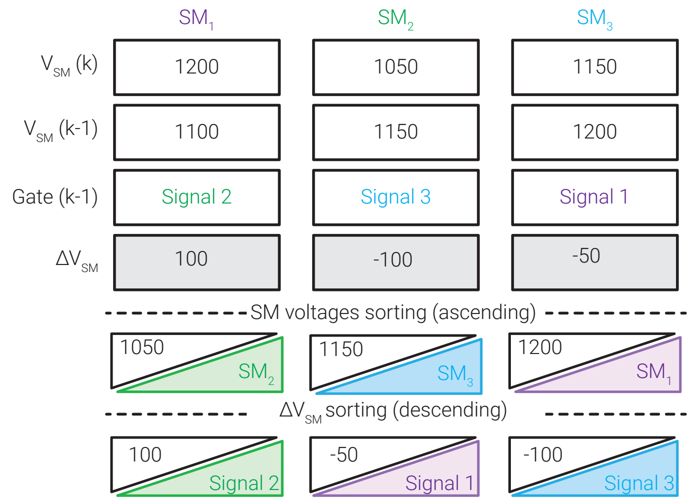

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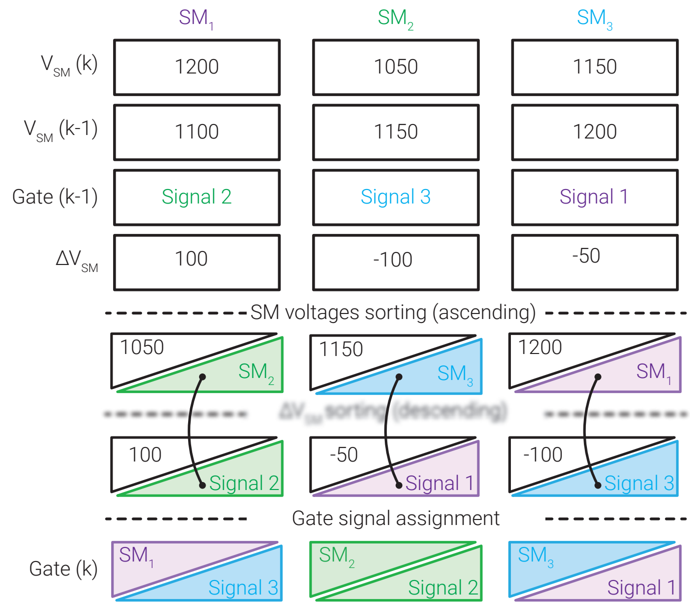
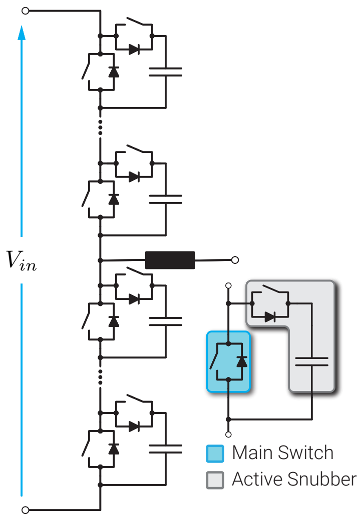
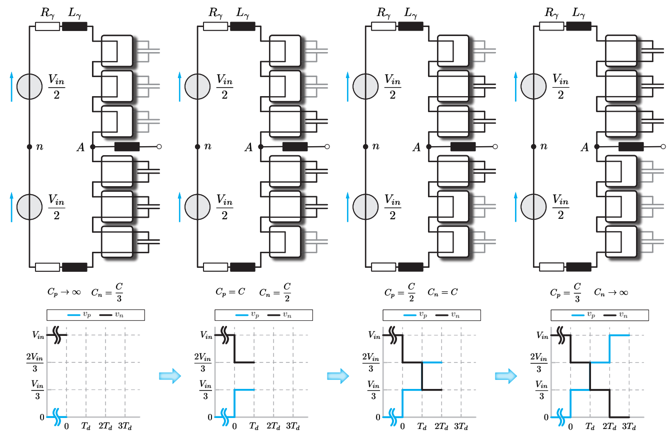
- $Gate(k)$ - Gate signal assigned to a SM in the observed switching period



- MMC-alike structure
- Branch inductors removed!
- SM = Main Switch + Active Snubber
- Sequential insertion/bypassing of SMs




▲ Quasi Two-Level Converter




▲ Example of the Q2L Converter transition (N=3)

# QUASI TWO-LEVEL (Q2L) CONVERTER

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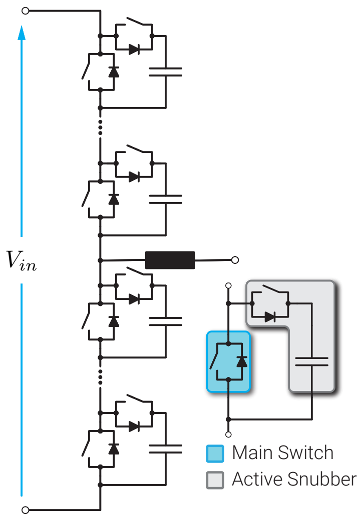


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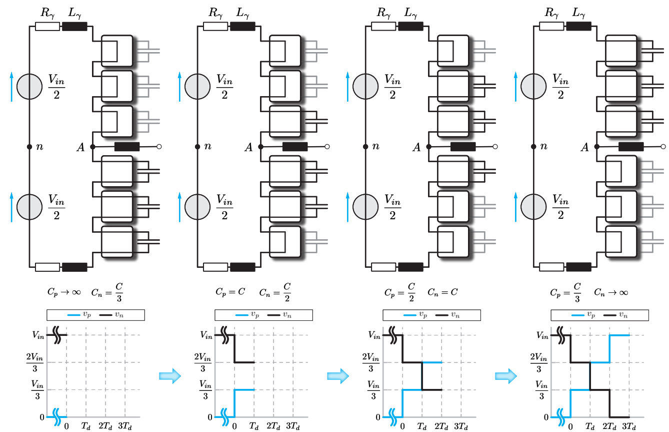


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Every dwell interval introduces new resonant parameters to the circuit!

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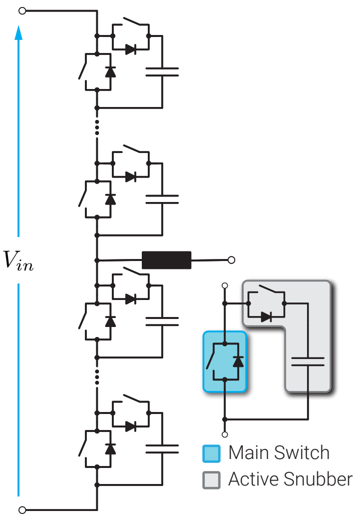


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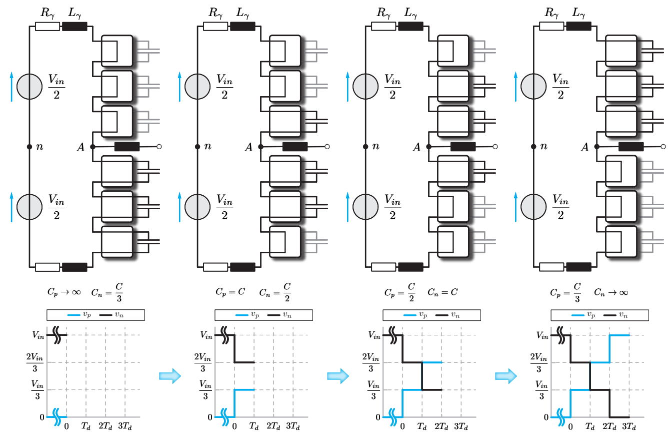


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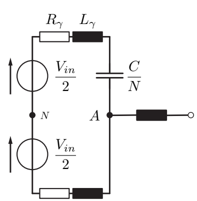

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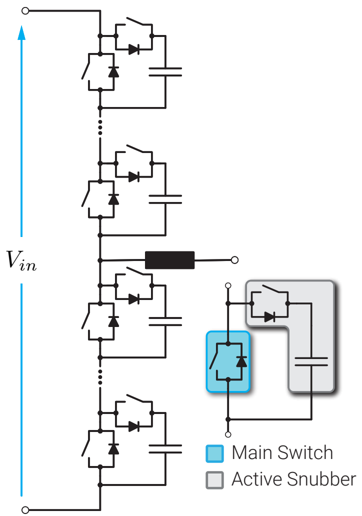


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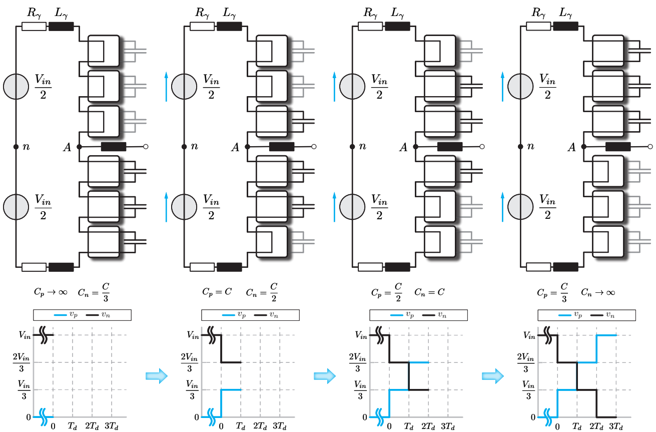


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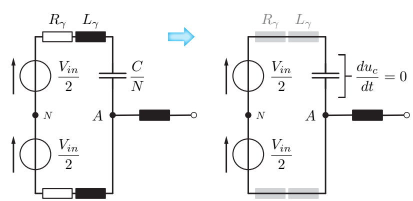

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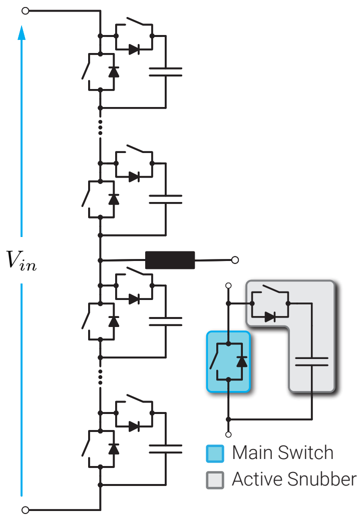


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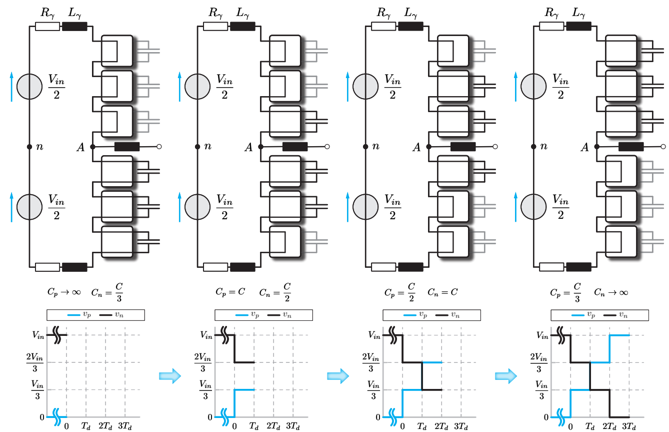


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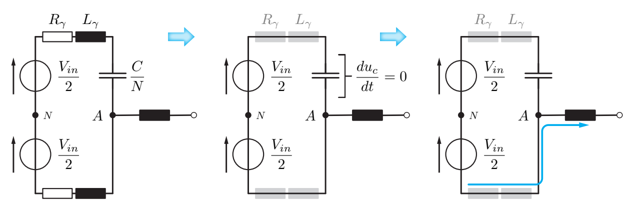
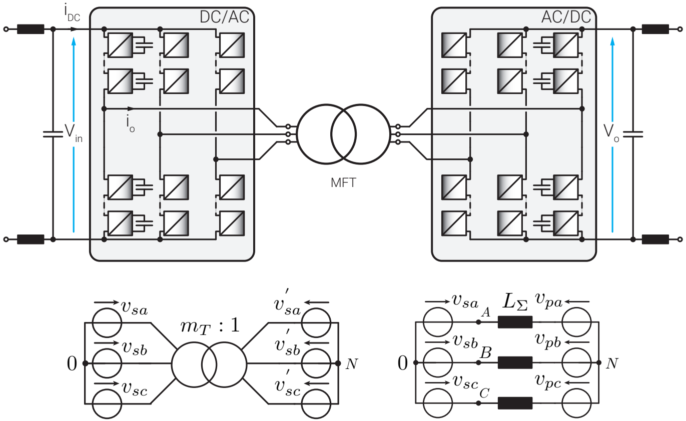
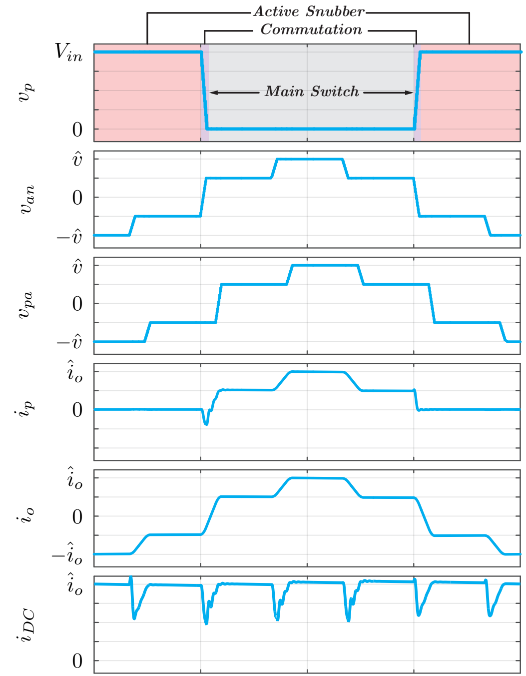



⟹ Output current drifts to a single branch. Common mode current does not exist!

# Q2L CONVERTER - PROS AND CONS




▲ Observed Q2L configuration




▲ Relevant waveforms of the Q2L converter operating as the 3PH-DAB

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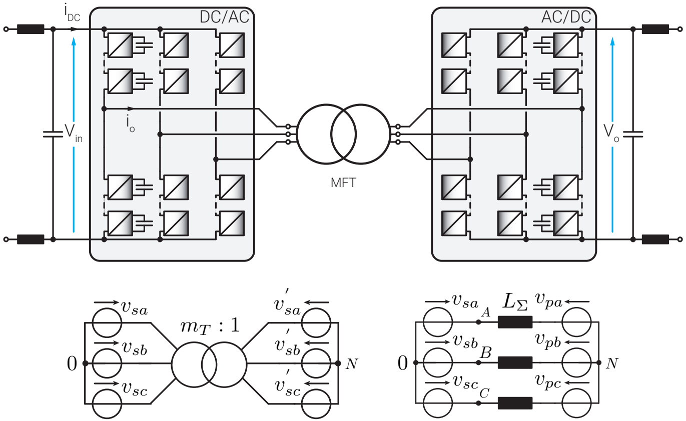
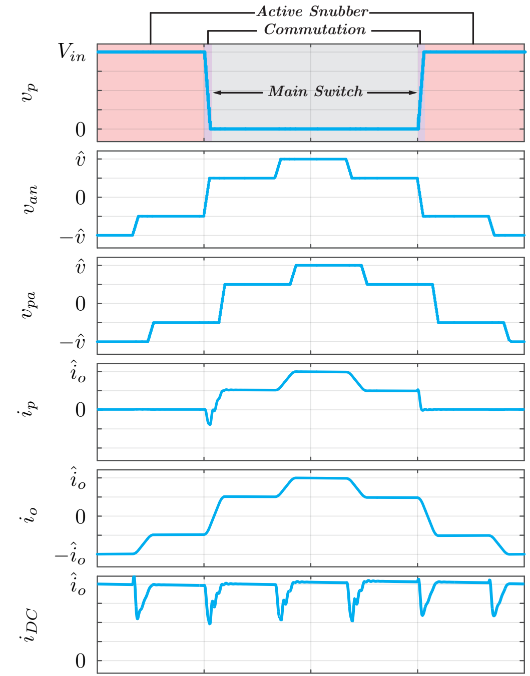



▲ Observed Q2L configuration

⇒ SM capacitor = "short-interval" energy buffer

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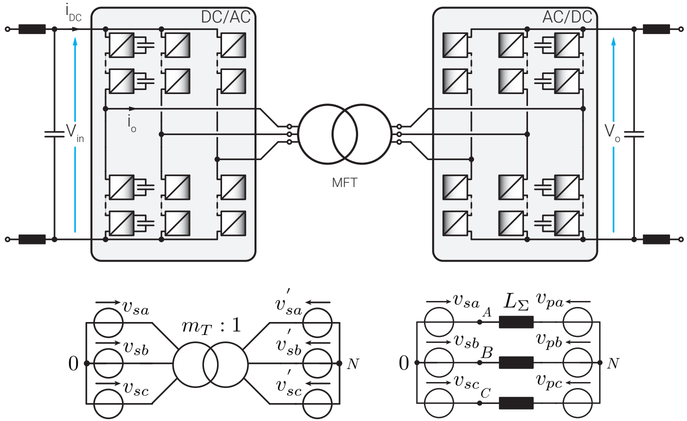


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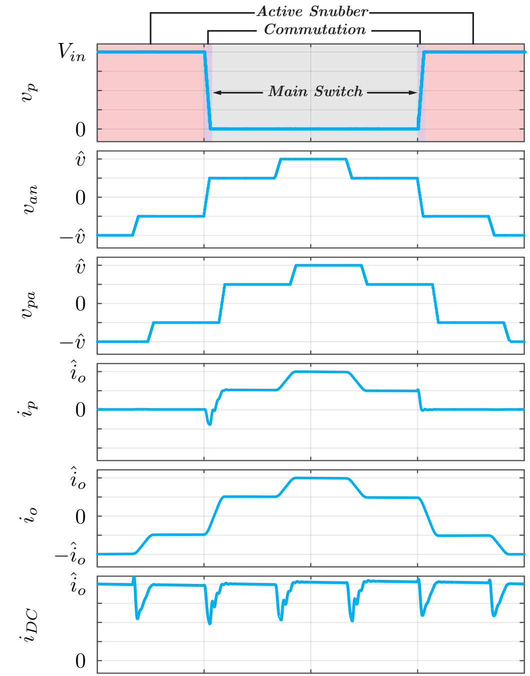


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**Pros**

- Significant reduction in submodule capacitance
- Converter size reduction (no branch inductors, small SM capacitance)
- Active snubber switch can be sized for half the rated current

**Cons**

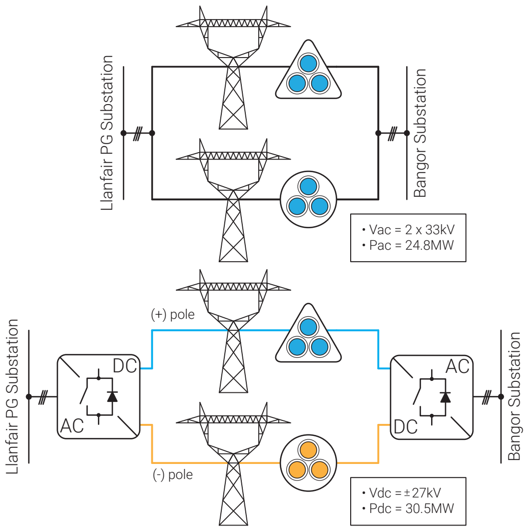
- Need for HV/MV input/output capacitor
- Complicated analysis of transition process/SM capacitance sizing
- SM capacitance sizing influenced by the branch stray inductance

# MMC-BASED DC-DC CONVERTERS UTILIZING SCOTT TRANSFORMER CONNECTION

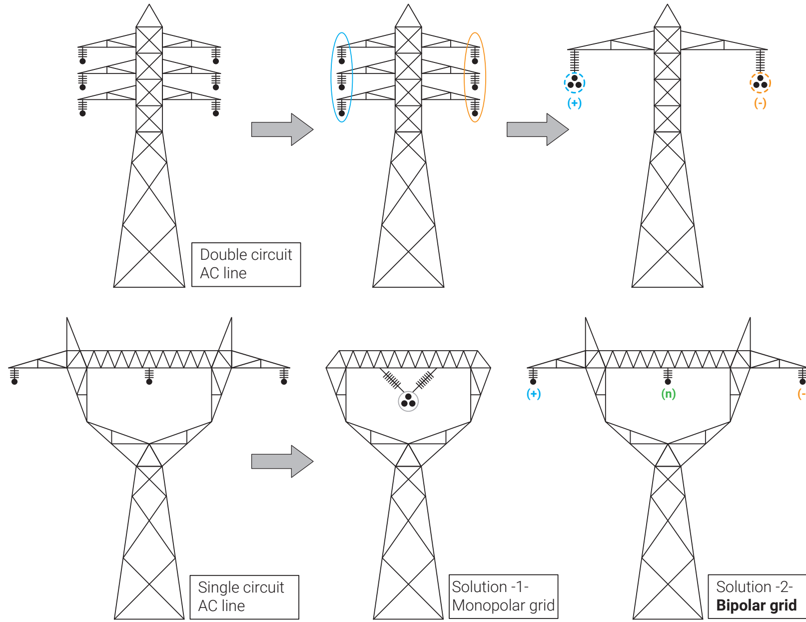
*Medium Frequency Conversion, High Power, Redundancy ...*

# CONVERSION OF AC LINES INTO DC

- Transmission capacity increase
- Employment of the existing conductors
- No change in tower foundations
- Possible tower head adjustment
- Possible isolator assemblies adjustment




▲ Angle DC Project - UK



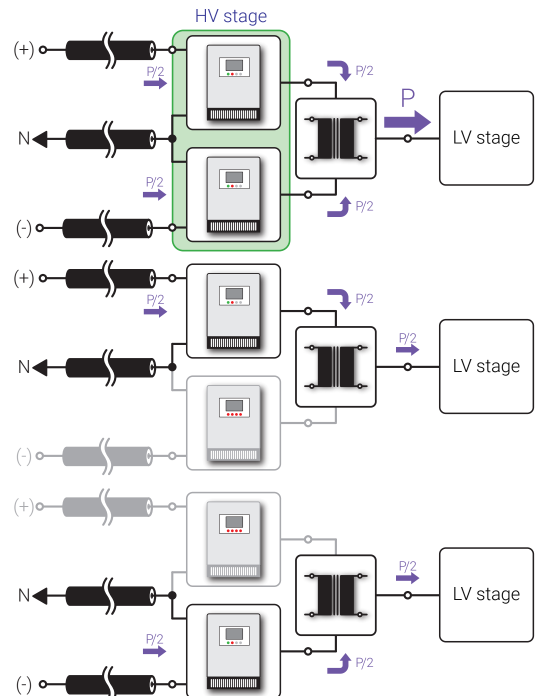

▲ Conversion of two typical AC lines into DC [46], [47], [48], [49]

# OBSERVED BIPOLAR SYSTEM

- Provided ratings

| Parameter | Value |
|---|---|
| Input voltage ($V_{in}$) | $\pm$20kV |
| Output voltage ($V_o$) | 1.5kV |
| Rated power ($P_{nom}$) | 10MW |
| Operating frequency ($f$) | 1kHz |

- **Redundancy**
- Converter structure considering given grid nature?
  - Topology
  - Operating principles and control
  - Operating frequency
  - Sizing principles considering given ratings
  - Constraints
  - Behavior under faults




▲ Generic structure of a converter to be employed within a bipolar grid

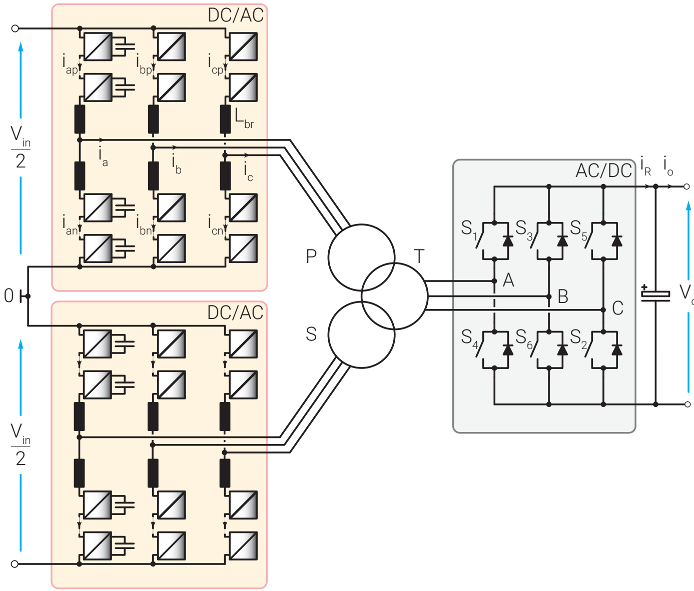
# SIX-STEP MMC-BASED HIGH POWER DC-DC CONVERTER

**Features:**

- Both stages switching at MFT operating frequency
- DAB operating principles
- Independent operation of the MMCs (ideally)
- Bidirectional topology
- Bipolar DC grids interface
- Redundant under faulty operating conditions
- Medium frequency operation

**Drawbacks?**

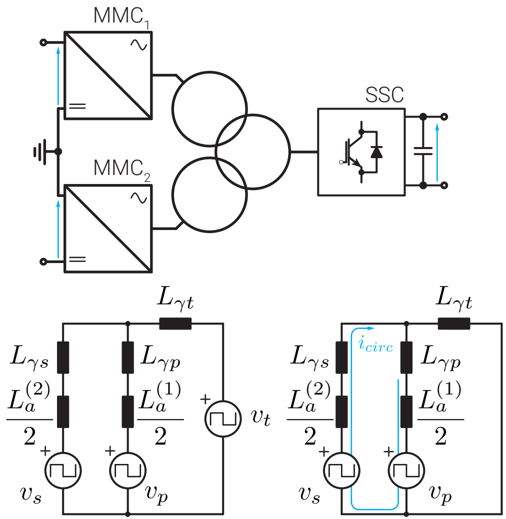
- Twelve arm inductors (or six coupled inductors)
- Magnetic coupling (circulating currents)



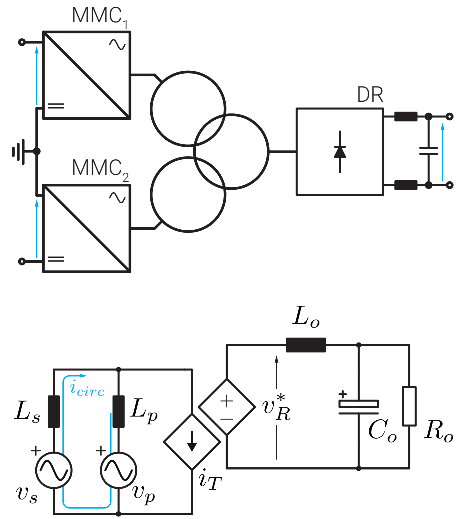

▲ Six-Step MMC-Based High Power DC-DC Converter [50]

# ORIGIN OF THE CIRCULATING CURRENTS

## Bidirectional Topology




## Unidirectional Topology



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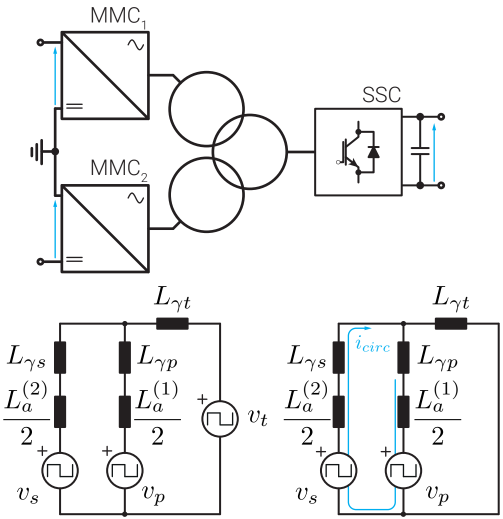
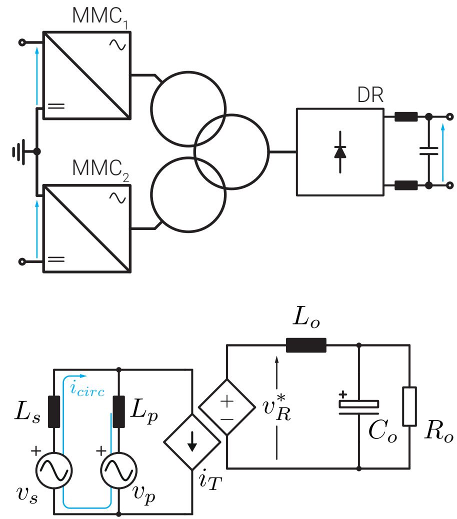



## Unidirectional Topology




⇒ $v_s \neq v_p \Rightarrow$ **Circulating currents!**

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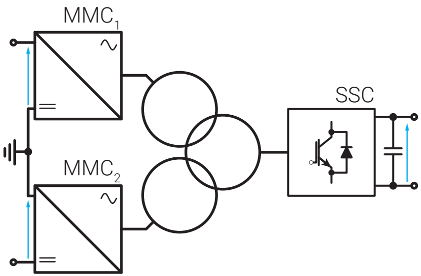


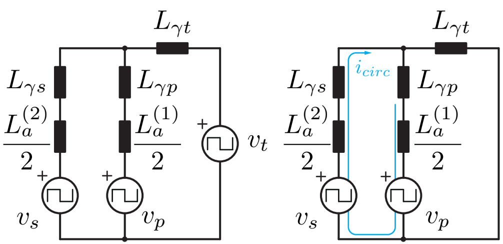


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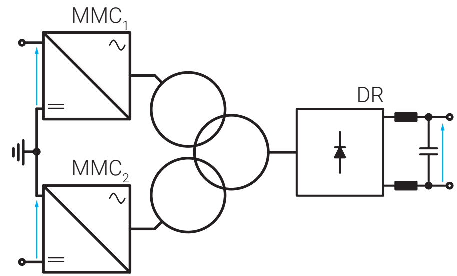
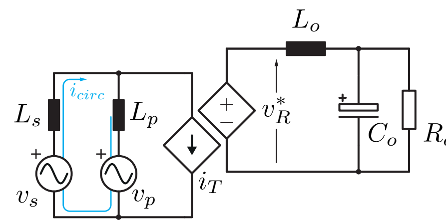


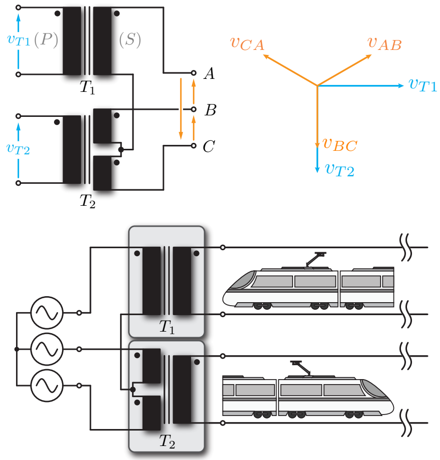

⇒ $v_s \neq v_p \Rightarrow$ **Circulating currents!**

However, magnetic coupling is what provides the means for the currents to circulate between windings.

↯ Magnetic coupling is to be avoided!

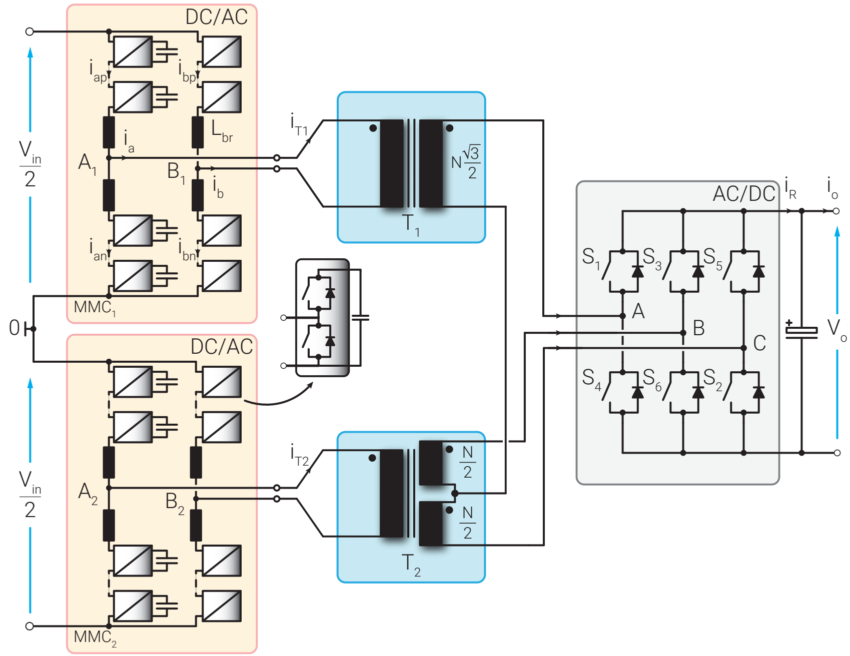
# BIDIRECTIONAL TOPOLOGY

# MMC-BASED BIDIRECTIONAL DC-DC CONVERTER EMPLOYING STC[2]




▲ Scott Transformer Connection

- 3PH 3W Tx ⇒ 2 x 1PH Tx
- Number of MMC branches reduction ($N_L$ ↓)
- Ability to operate in a pure rectifier mode
- Medium frequency operation




▲ MMC-Based High Power DC-DC Converter Employing Scott Transformer Connection [51]

[2] S. Milovanović, D. Dujić, "MMC-Based High Power DC-DC Converter Employing Scott Transformer." PCIM Europe 2018

# Operating principles

- MMCs independent operation

$$V_{T1} = m_{T1}\frac{V_{AB} - V_{CA}}{2}$$
$$V_{T2} = m_{T2}V_{BC}$$

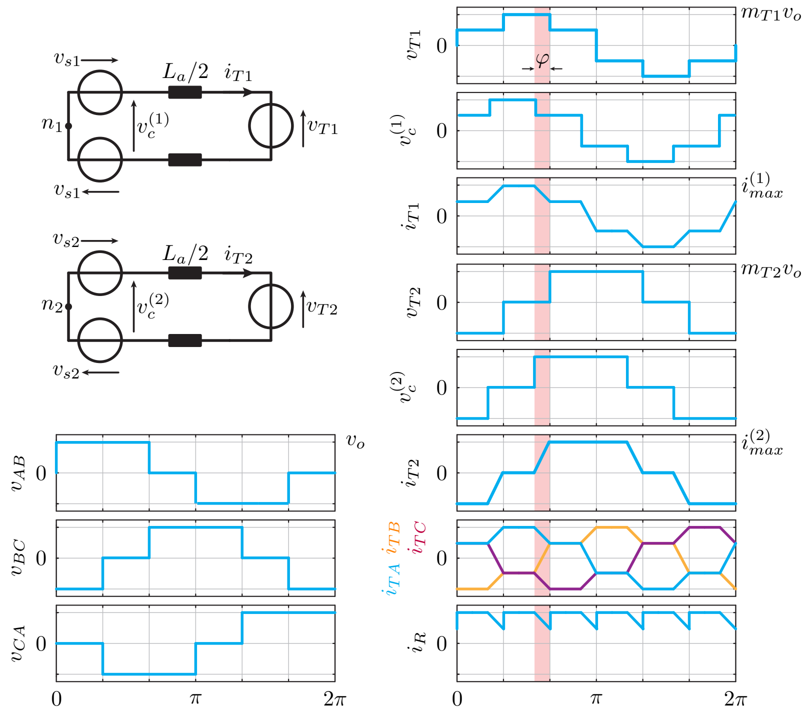
- Suitable HV side voltages ($V_{c1}$, $V_{c2}$)?
- DAB behavior (phase modulated converter)

$$P_1 = \frac{V_o^2 m_{T1}^2}{\omega L_a}\varphi_1\left(\frac{1}{2} - \frac{3|\varphi_1|}{8\pi}\right)$$
$$P_2 = \frac{V_o^2 m_{T2}^2}{\omega L_a}\varphi_2\left(\frac{2}{3} - \frac{|\varphi_2|}{2\pi}\right)$$

---

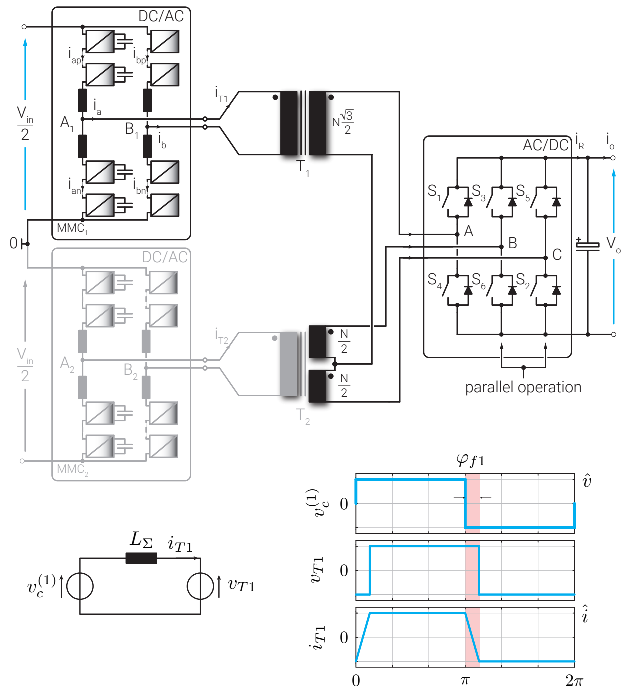
$$\left(m_{T1} == \frac{2}{\sqrt{3}}m_{T2}\right) \wedge \left(\varphi_1 == \varphi_2\right)$$
$$\Rightarrow P_1 = P_2$$

- Bidirectional topology
- Fundamental frequency switching
- Redundant under faults

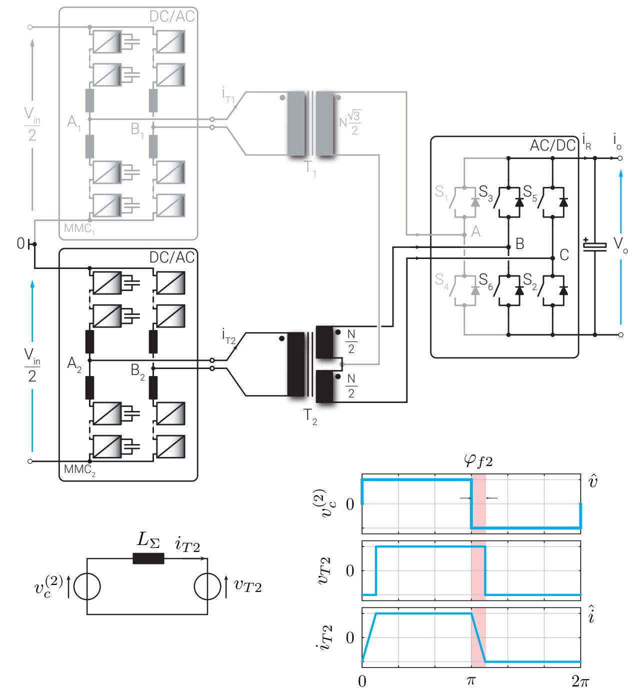



▲ Converter idealized operating waveforms

# OPERATION UNDER FAULTS




▲ Converter operation in the case of "Minus" DC pole malfunction

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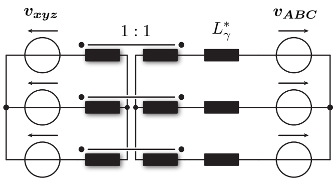
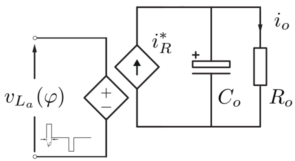
- 3PH-DAB equivalent model




$$\boxed{\begin{array}{c} \boldsymbol{v_{xyz}} = \boldsymbol{v_{ABC}} e^{j\varphi} \\ L_\gamma^* = \frac{L_a}{2m_{T2}^2} \end{array}}$$

- Linearization

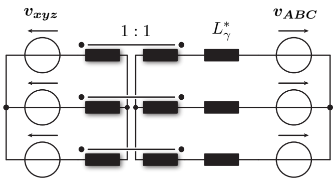



▲ SSC equivalent circuit seen from the LV side

$$V_o\overline{i_R} = 2\frac{m_{T1}^2 V_o^2}{\omega L_a}\underbrace{\varphi\left(\frac{1}{2} - \frac{3\varphi}{8\pi}\right)}_{\textit{Linearized}!}$$

$$\Rightarrow \overline{i_R} \approx \frac{7m_{T1}^2 V_o^*}{8\omega L_a}\varphi$$

- 3PH-DAB equivalent model

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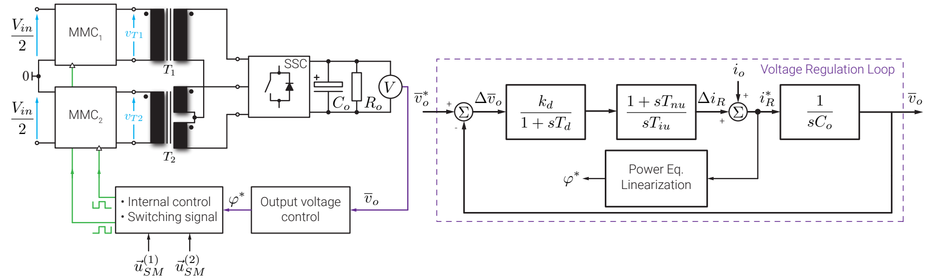
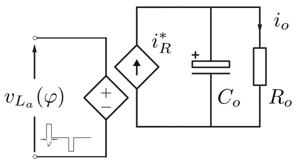



▲ STC-based SST Control block scheme

- Linearization

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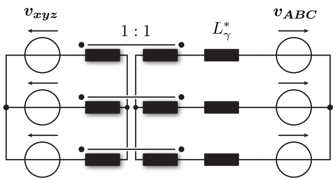


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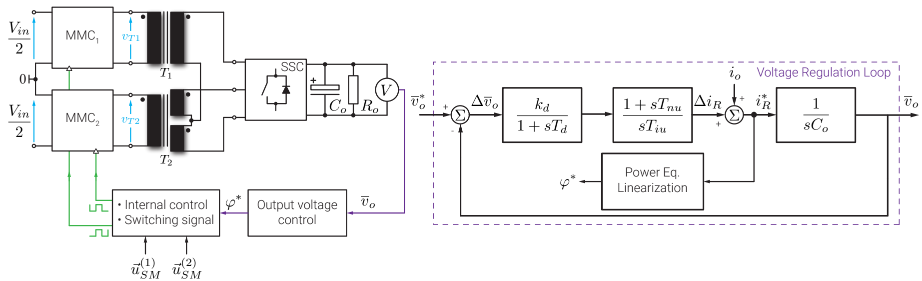


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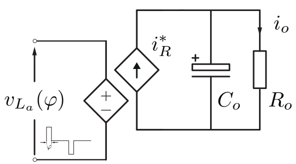



▲ SSC equivalent circuit seen from the LV side

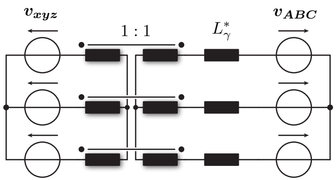
? What if $P_1 \neq P_2$ for any reason?

$$V_o \overline{i_R} = 2\frac{m_{T1}^2 V_o^2}{\omega L_a} \underbrace{\varphi\left(\frac{1}{2} - \frac{3\varphi}{8\pi}\right)}_{Linearized!}$$

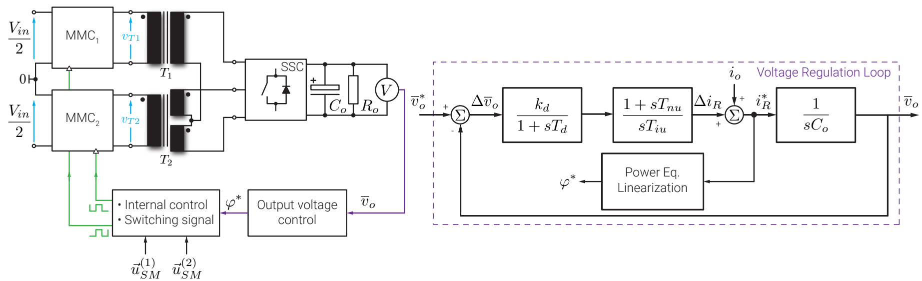
$$\Rightarrow \overline{i_R} \approx \frac{7 m_{T1}^2 V_o^*}{8\omega L_a}\varphi$$

# CONTROL

- 3PH-DAB equivalent model

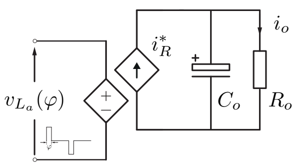



$$v_{xyz} = v_{ABC} e^{j\varphi}$$
$$L_\gamma^* = \frac{L_a}{2 m_{T2}^2}$$




▲ STC-based SST Control block scheme

- Linearization




▲ SSC equivalent circuit seen from the LV side

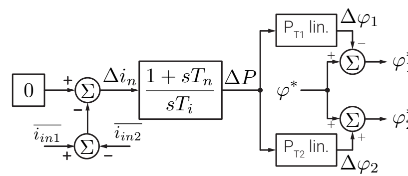
$$V_o \overline{i_R} = 2 \frac{m_{T1}^2 V_o^2}{\omega L_a} \underbrace{\varphi\left(\frac{1}{2} - \frac{3\varphi}{8\pi}\right)}_{Linearized!}$$

$$\Rightarrow \overline{i_R} \approx \frac{7 m_{T1}^2 V_o^*}{8\omega L_a} \varphi$$

? What if $P_1 \neq P_2$ for any reason?

$$\Delta P_{T1}^{lin} = \frac{7 V_0^2 m_{T1}^2}{16\omega L_a} \Delta\varphi_1$$

$$\Delta P_{T2}^{lin} = \frac{7 V_0^2 m_{T2}^2}{12\omega L_a} \Delta\varphi_2$$




▲ Power balance loop

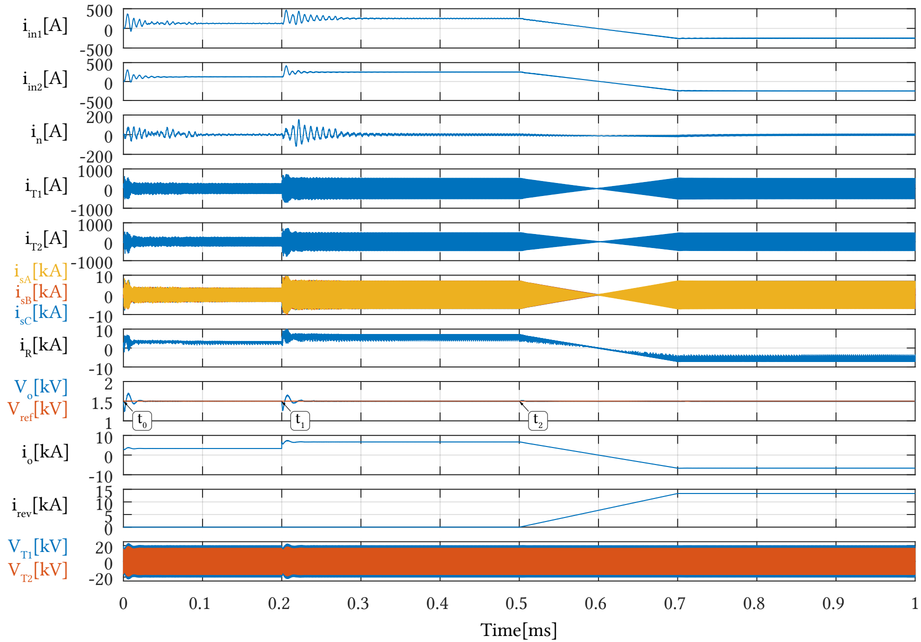
⇒ Additional control compensates small power mismatches!

# SIMULATION RESULTS (I)

**Table 1** Simulated system ratings

| Parameter | Value |
|---|---|
| Input voltage ($V_{in}$) | ±20kV |
| Output voltage ($V_o$) | 1.5kV |
| Rated power ($P_{nom}$) | 10MW |
| Operating frequency ($f$) | 1kHz |

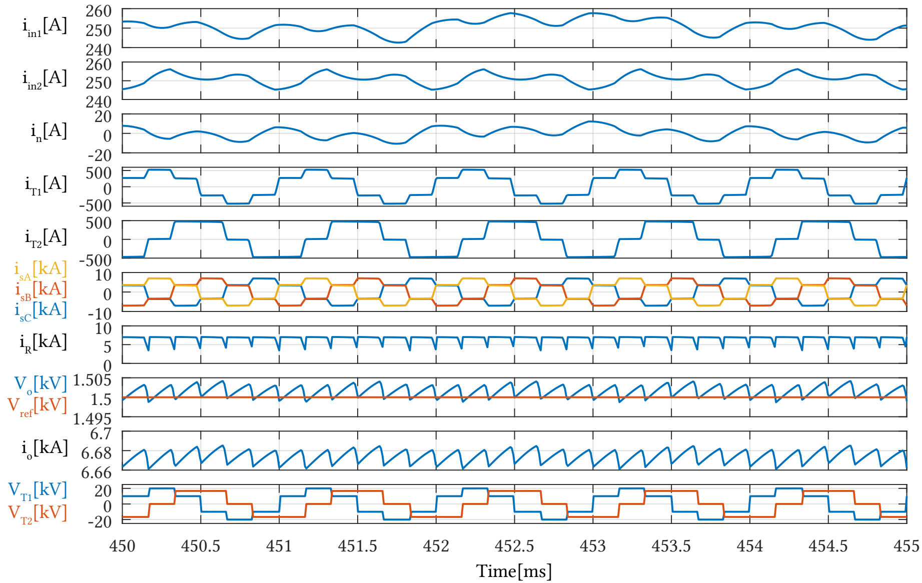
- $i_{in1}$ → $MMC_1$ input current
- $i_{in2}$ → $MMC_2$ input current
- $i_{in}$ → neutral conductor current
- $i_{T1}$ → $T_1$ P-winding current
- $i_{T2}$ → $T_2$ P-winding current
- $i_S$ → LV stage 3PH-currents
- $i_R$ → SSC output current
- $V_o$ → load voltage
- $i_o$ → load current
- $i_{rev}$ → LV side current injection
- $V_{T1}$ → $T_1$ P-winding voltage
- $V_{T2}$ → $T_2$ P-winding voltage




▲ Converter operating waveforms

# SIMULATION RESULTS (II)

- $i_{in1}$ → MMC$_1$ input current
- $i_{in2}$ → MMC$_2$ input current
- $i_{in}$ → neutral conductor current
- $i_{T1}$ → T$_1$ P-winding current
- $i_{T2}$ → T$_2$ P-winding current
- $i_S$ → LV stage 3PH-currents
- $i_R$ → SSC output current
- $V_o$ → load voltage
- $i_o$ → load current
- $i_{rev}$ → LV side current injection
- $V_{T1}$ → T$_1$ P-winding voltage
- $V_{T2}$ → T$_2$ P-winding voltage

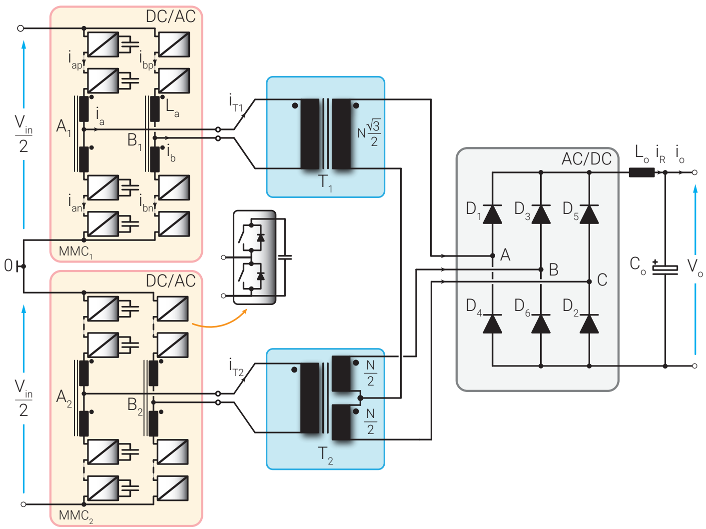



▲ Converter operating waveforms during five fundamental cycles

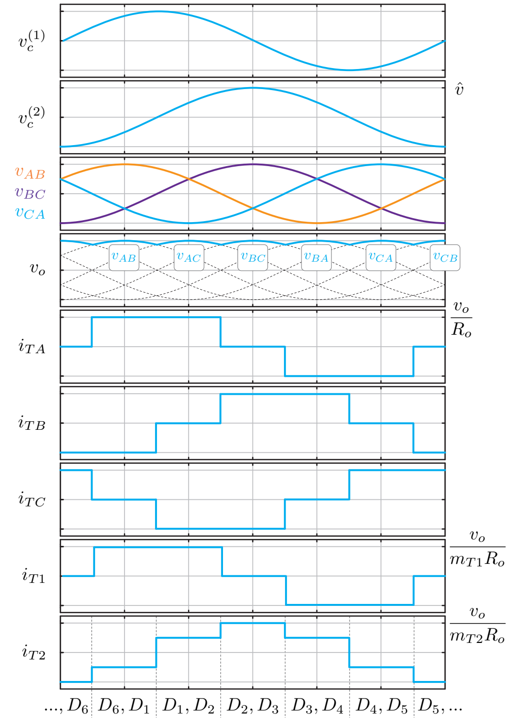
# UNIDIRECTIONAL TOPOLOGY

# MMC-BASED HIGH POWER UNIDIRECTIONAL DC-DC CONVERTER

- No magnetic coupling between Tx windings
- Parameters mismatch robustness
- Sinusoidal operation mode!




▲ MMC-based High-Power Unidirectional DC-DC Converter

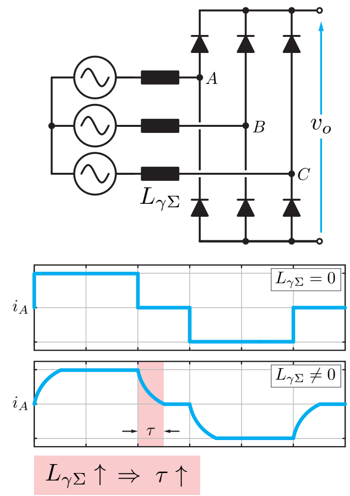



▲ Converter idealized operating waveforms

.

**Adverse effects of the arm inductance**

- Output voltage drop
- Increased commutation time



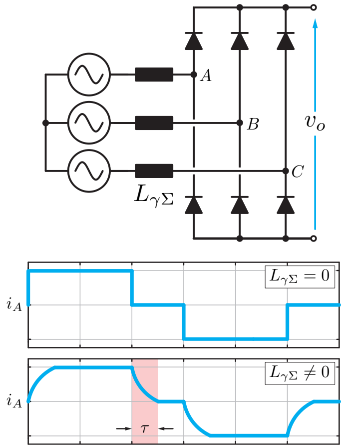

▲ Phase inductance effect on diode rectifier current waveform

# MMC INDUCTORS COUPLING?

.

**Adverse effects of the arm inductance**

- Output voltage drop
- Increased commutation time




$$L_{\gamma\Sigma} \uparrow \;\Rightarrow\; \tau \uparrow$$

▲ Phase inductance effect on diode rectifier current waveform

MMC branch inductors might limit converter operating frequency!

# MMC INDUCTORS COUPLING?

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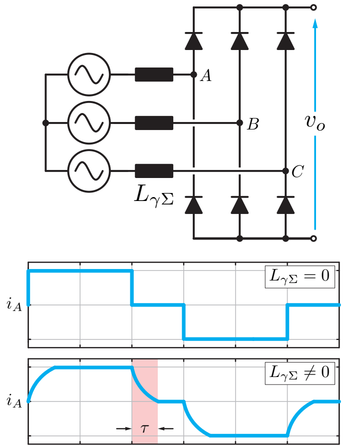
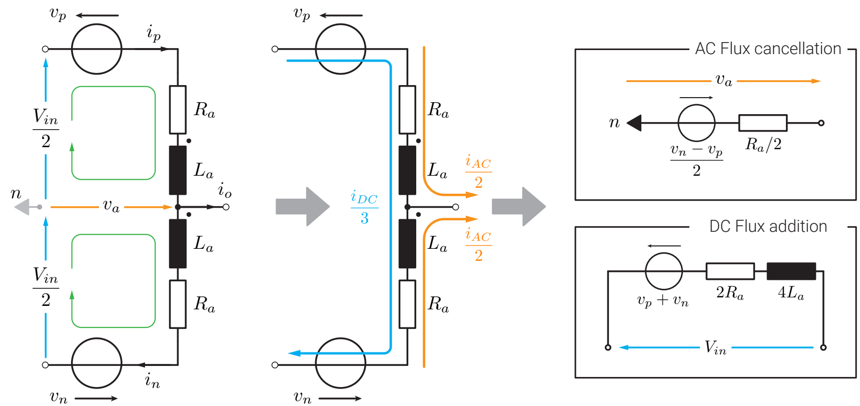
**Adverse effects of the arm inductance**

- Output voltage drop
- Increased commutation time




$$L_{\gamma\Sigma} \uparrow \;\Rightarrow\; \tau \uparrow$$

▲ Phase inductance effect on diode rectifier current waveform



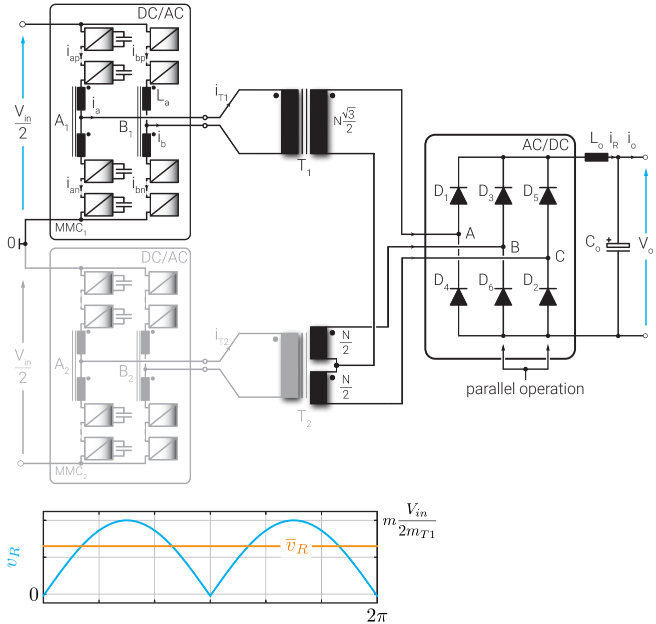

▲ AC/DC equivalent circuits of a MMC leg with coupled inductors (ideal coupling)

**Benefits of arm inductors coupling**

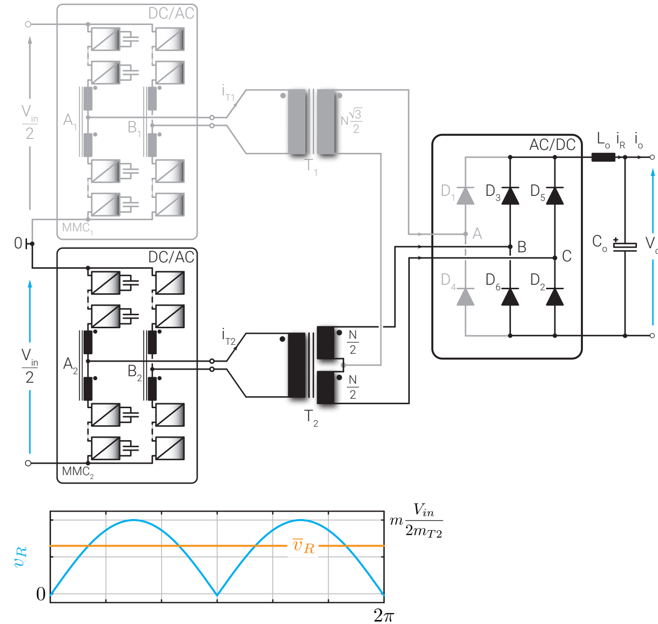
- Reduced AC side inductance (ideal voltage source behavior)
- Increased DC side inductance (lower input current ripple)
- Reduced output voltage drop (reduced rectifier commutation time)

MMC branch inductors might limit converter operating frequency!

# OPERATION UNDER FAULTS




▲ Converter operation in the case of "Minus" DC pole malfunction



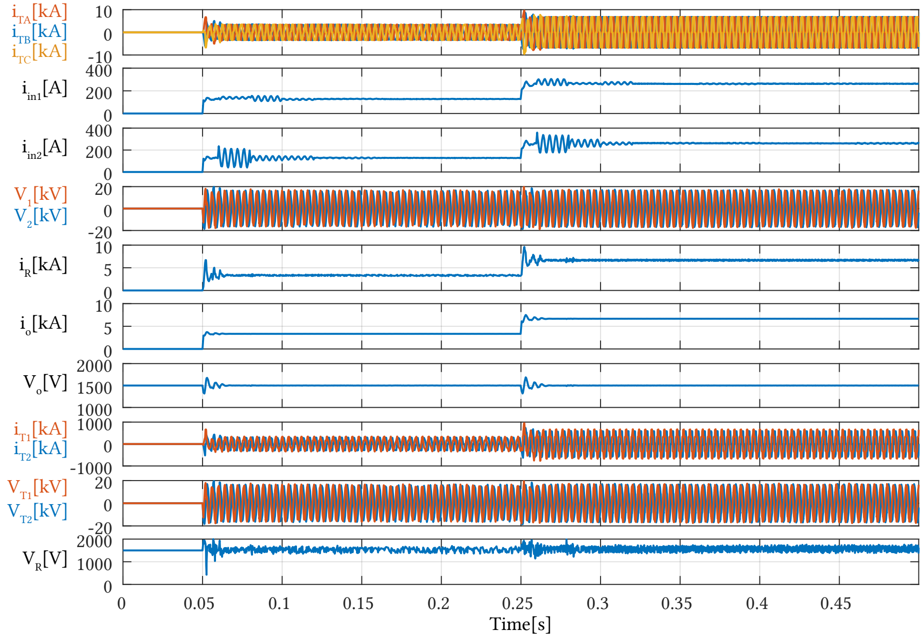

▲ Converter operation in the case of "Plus" DC pole malfunction

# SIMULATION RESULTS (I)

**Table 2** Simulated system ratings

| Parameter | Value |
|---|---|
| Input voltage ($V_{in}$) | ±20kV |
| Output voltage ($V_o$) | 1.5kV |
| Rated power ($P_{nom}$) | 10MW |
| Operating frequency ($f$) | 250Hz |

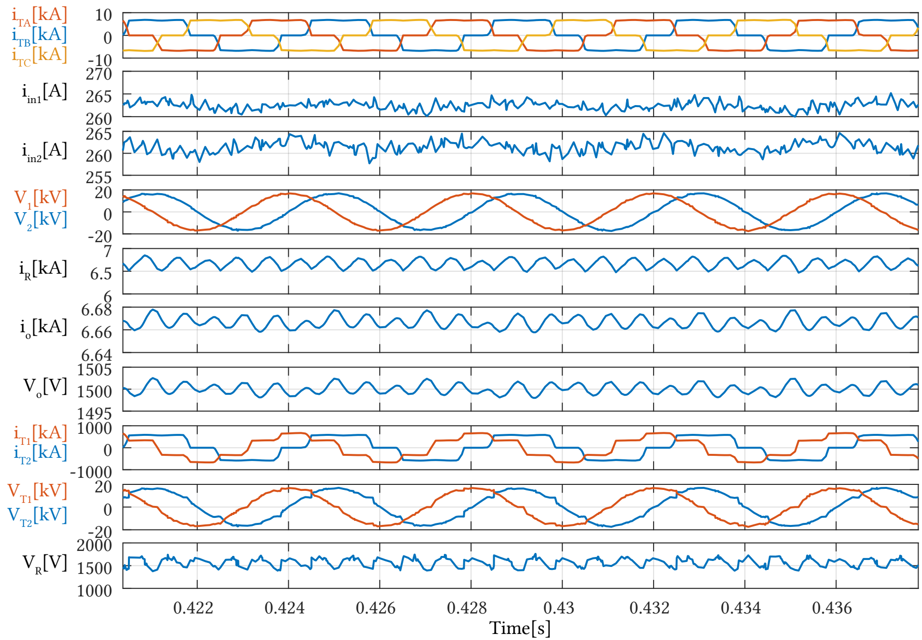
- $i_T$ → LV-stage 3PH - currents
- $i_{in1}$ → $MMC_1$ input current
- $i_{in2}$ → $MMC_2$ input current
- $V_1$ → $MMC_1$ AC voltage
- $V_2$ → $MMC_2$ AC voltage
- $i_R$ → DR output current
- $i_o$ → load current
- $V_o$ → load voltage
- $i_{T1}$ → $T_1$ P-winding current
- $i_{T2}$ → $T_2$ P-winding current
- $V_{T1}$ → $T_1$ P-winding voltage
- $V_{T2}$ → $T_2$ P-winding voltage
- $V_R$ → DR output voltage




▲ Converter operating waveforms

# SIMULATION RESULTS (II)

- $i_T$ → LV-stage 3PH - currents
- $i_{in1}$ → $MMC_1$ input current
- $i_{in2}$ → $MMC_2$ input current
- $V_1$ → $MMC_1$ AC voltage
- $V_2$ → $MMC_2$ AC voltage
- $i_R$ → DR output current
- $i_o$ → load current
- $V_o$ → load voltage
- $i_{T1}$ → $T_1$ P-winding current
- $i_{T2}$ → $T_2$ P-winding current
- $V_{T1}$ → $T_1$ P-winding voltage
- $V_{T2}$ → $T_2$ P-winding voltage
- $V_R$ → DR output voltage



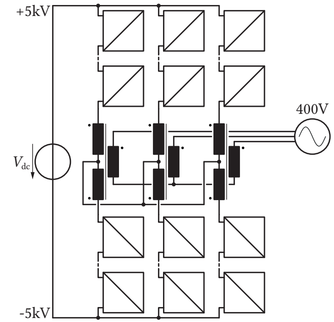

▲ Converter operating waveforms during five fundamental cycles

# SUMMARY

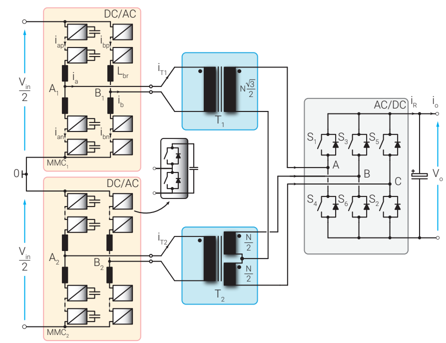
## Modular Multilevel Converter

- Modular design easily scalable for higher voltages
- Flexible and adaptable for different conversion needs
- Efficient
- HVDC (early adopter)
- STATCOM, FACTS, RAIL INTERTIES, MV DRIVES
- Can serve MV and HV applications!
- Unlimited research opportunities...

▲ HVDC Light valve hall from ABB.




▲ Galvanically Isolated Modular Converter




▲ High Power DC-DC Converter Employing Scott Transformer Connection

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